REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
31-03-2011	REPRINT	

4. TITLE AND SUBTITLE
Demonstrations and Science Experiment (DSX) Space Weather Experiment (SWx)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63401F

6. AUTHORS
J. A. Fennelly

5d. PROJECT NUMBER
5021

5e. TASK NUMBER
RS

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory /RVBXR
29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-HA-TR-2011-1018

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution unlimited.

20110509006

13. SUPPLEMENTARY NOTES
Reprinted from *Solar Physics and Space Weather Instrumentation III*, edited by Silvano Fineschi, Judy A. Fennelly, *Proc. of SPIE* Vol. 7438, 743805. doi:10.1117/12.828321. © 2009 SPIE

14. ABSTRACT
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15. SUBJECT TERMS
Space physics Van Allen radiation belts Space environment Energetic particle distribution Slot region Medium earth orbits Radiation environment models

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCL	UNCL	UNCL	UNL	11	Judy A. Fennelly

19B. TELEPHONE NUMBER *(Include area code)*

Demonstration and Science Experiment (DSX) Space Weather Experiment (SWx)

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ABSTRACT

The Air Force Research Laboratory has developed the Demonstration and Science Experiments (DSX) to research technologies needed to significantly advance the capability to operate spacecraft in the harsh radiation environment of medium-earth orbits (MEO). The ability to operate effectively in the MEO environment significantly increases the capability to field space systems that provide high-speed satellite-based communication, lower-cost GPS navigation, and protection for satellites from space weather effects. The one of DSX's physics based research areas is the Space Weather Experiment (SWx), characterizing and modeling the space radiation environment in MEO, an orbital regime attractive for future space missions.

Keywords: Space physics, Van Allen radiation belts, space environment, energetic particle distribution, slot region, Medium Earth Orbits, radiation environment models

1. INTRODUCTION

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate has designed and matured the Demonstration and Science Experiments (DSX) as an experimental space mission that is anticipated to appreciably increase the capability of spacecraft operations in the radiation environment encountered by medium-earth orbits (MEO), at an altitude range from 6,000 to 15,000 km [1]. The discovery of the earth's radiation belts just over fifty years ago and the subsequent investigations of that region have led to remarkable advances in our understanding the near earth environment. It is acknowledged that trapped energetic particles in the earth's magnetic field in this region present a significant hazard to spacecraft operating in this environment [2]. This region is made up of the inner radiation belt consisting mainly of protons and the outer radiation belt consisting of energetic electrons. The radiation belts' energetic particle population is known to have great fluctuations over the 11 year solar cycle. The region between the two radiation belts is called the "slot region." This region was once thought to be a relatively benign environment for spacecraft since observations indicated that it encompassed a space of relatively low energetic particle fluxes, however the slot region is very dynamic. It is essential that we improve our ability to predict radiation exposures in this region.

The results gathered from the DSX mission are projected to greatly increase our scientific knowledge of the "slot region" resulting greater capability reducing the cost of manufacturing and operating space systems. Currently, the Global Positioning System (GPS), a satellite-based navigation system made up of a network of 24 satellites placed into orbit by the U.S. Department of Defense, which operates in this region. It is expected that an improve understanding of the dynamics of this region would translate into cost efficient spacecraft designs, which while reducing the overall cost would also increase the spacecraft's lifetime.

DSX in its nominal orbit traverses the slot region daily as shown in Figure 1. The DSX was designed to explore a large swath of the inner magnetosphere, as it travels through the outer region of the inner proton belt, the slot region, and the inner regions of the outer electron belt. In particular, DSX is expected to remain largely in the slot region, which is a largely unexplored region by previous scientific satellite missions. DSX consists of three basic research experiments: 1) wave particle interaction experiment (WIPx); 2) space weather experiment (SWx) and; 3) space environmental effects experiment (SFx) [1]. The WIPx researches the physics of very low frequency (VLF, 0.1-50 kHz) wave-particle interactions and the role VLF plays in modulating the particle populations in the radiation belts and slot region. The SWx is designed to characterize, map and model the space radiation environment for MEO. The combination of WIPx, SWx and SFx experiments onto the single DSX platform provides a cost-effective opportunity for research, since all three experiments have common requirements and goals. Each experiment requires a 3-axis stabilized spacecraft bus, a suite of sensors that can measure electron and protons over a large energy range and extended duration in a MEO orbit [1].

Solar Physics and Space Weather Instrumentation III, edited by Silvano Fineschi, Judy A. Fennelly, Proc. of SPIE Vol. 7438, 743805 · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.828321

The Wave Particle Experiment, WIPx, is the DSX primary experiment. The WIPx is comprised of several instruments including the Wave-induced Precipitation of Electron Radiation (WIPER) Broad-band Receiver (BBR) designed to measure the natural and man-made ELF, VLF, and LF signals in the inner magnetosphere. Moreover, the WIPx measures two axis of the electric field and all three axis of the magnetic field. The DC Vector Magnetometer (VMAG) that measures the *in situ* magnetic field is used by the SWx in its research efforts [1].

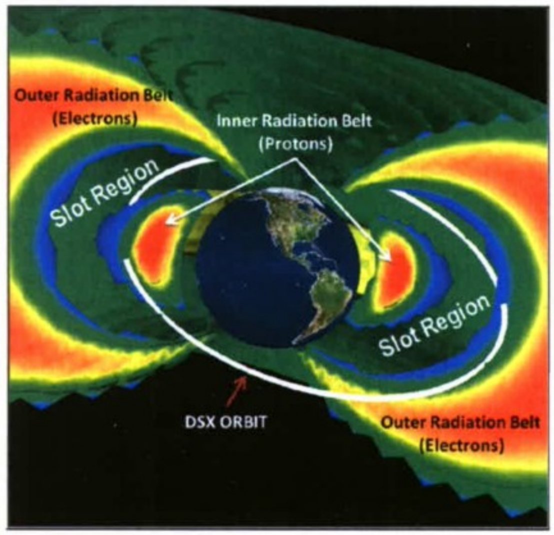


Fig. 1. DSX nominal orbit (6,000 by 12,000 km, inclination 28°) allows it to pass through edges of both the outer and inner radiation belts. A large portion of DSX's orbit is spent in the slot region. The relative flux intensities of the radiation belts are indicated by red as the most intense and green as the least intense.

The DSX uses a modular structure that allows for launch as either a primary or secondary satellite payload, making it compatible with multiple conventional launch vehicles including the Evolved Expendable Launch Vehicle (EELV). The capability to launch with an EELV led to a unique design feature for the DSX spacecraft. DSX uses an EELV Secondary Payload Adapter (ESPA) ring as the primary bus structure with two modules permanently attached [3], one is the Avionics Module (AM) and the other is the Payload Module (PM) (shown in Figure 2). The Avionics Module provides the avionics, tracking telemetry and command (TT&C), attitude determination and control system (ADCS), command and data handling (C&DH), and power management and distribution. The Payload Module contains all but one of the experiment payloads; the High Energy Particle Spectrometer (HEPS) is located on the AM. The PM also includes the two deployable booms (see Figure 2). The DSX Host Spacecraft Bus (HSB) is comprised of the AM, PM and the ESPA ring [3]. Normally, the ESPA ring would remain attached to the launch vehicle upper stage to facilitate deployment of microsatellites, but this is not the case for the DSX. However, the DSX HSB uses the ESPA ring as the structure supporting the AM and PM sections.

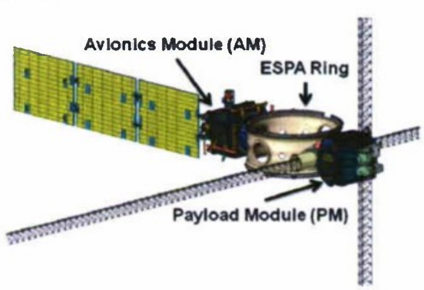


Fig. 2. DSX spacecraft is shown in a deployed configuration.

The DSX conducts the three experiments in the radiation belts between magnetic L-shells of approximately 2-3. The distances in this region are measured in terms of L (or L-shell). Basically, L is the equatorial crossing point of a magnetic field line passing through that magnetospheric location in units of earth radii (see Figure 3). L is used because most magnetospheric plasma parameters tend to align along magnetic field lines, i.e. L-shells [4]. L-shells extend from the northern hemisphere to the southern hemisphere and tend to trap and retain plasma through the processes of magnetic mirroring.

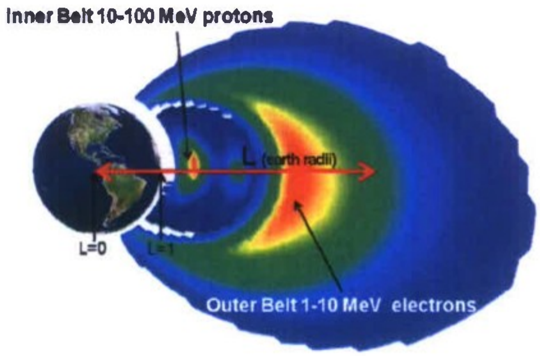


Fig 3. The equatorial crossing point of a magnetic field line passing through a magnetospheric location is measured in units of earth radii know as L.

2. SPACE WEATHER EXPERIMENT (SWx)

The Space Weather Experiment (SWx) on DSX is one of the most comprehensive experiments put into orbit to measure both the angular and the energy distribution of protons and electrons in the inner magnetosphere. The inner magnetosphere consists of the Van Allan radiation belts (magnetically trapped particles), plasmasphere, plasmapause, and ring current. The high resolution of temporal and spatial distributions of the angular and energy spectra of the electrons and protons provides valuable information needed to further understanding of the inner magnetosphere structure and dynamics. This information also has great value to the DSX WIPx experiment, the wave-particle interactions experiment to achieve its objectives. Further, time dependent, high-resolution databases are needed to build a better climatology, specification and forecast models that enable future space missions in the medium Earth orbit regime to enable better spacecraft designed to withstand the harsh environment, which increases reliability and lifetime as well as reduce costs.

There are five SWx sensors; the Low Energy Electrostatic Analyzer (LEESA), Low-Energy Imaging Particle Spectrometer (LIPS), Compact Environmental Anomaly Sensor (CEASE), High Energy Imaging particle Spectrometer (HIPS), and High Energy Particle Spectrometer (HEPS). The location of these experiments on the stowed DSX spacecraft is shown in Figure 4. The DC Vector Magnetometer (VMAG), a WIPx payload, data supports the DSX SWx is also shown in Figure 4. The SWx sensors provide the most comprehensive particle energy coverage ever flown in a MEO orbit. The current expected energy coverage for both electron and protons are shown in Figure 5. Final coverage energy range will not be known until all sensor calibrations have been completed prior to delivery for spacecraft integration.

Another important measurement set for the SWx is made by LEESA, LIPS and HIPS, which measures the angle of arrival of electrons and protons. This is an important measurement since charge particles moving in earth's magnetic field travel in spiral orbits around theses field lines. The angle between the particles spiral orbit and the direction of the magnetic field line is referred to as the pitch angle. It is the pitch angle that determines how far the particle travels down into the ionosphere. The lower a charge particle travels down into the ionosphere the higher the probability that it sufferers a collision with another particle and not return to the inner magnetosphere [4]. From the angle of arrival measurements and the VMAG magnetic field measurements the particle's pitch angles are calculated, thus producing angular particle distributions. With the particle flux distribution with respect to the local pitch angle it is then possible to estimate the global particle distribution by mapping techniques.

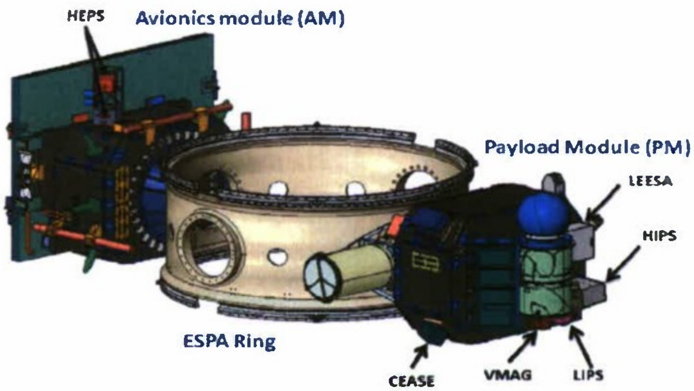


Fig 4. DSX stowed configuration showing the location of the SWx sensors, including the WIPx VMAG sensor.

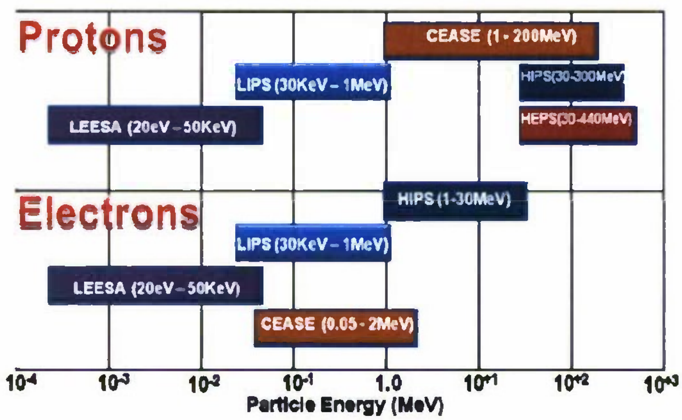


Fig 5. Current approximated DSX SWx expected energy range coverage.

DSX's orbital regime presents sever constraints for any space system exposed to this harsh environment, which results in a restrictive feature in spacecraft design that keeps satellite onboard processing power and memory at a level that lags consumer computing technology. Current spacecraft designs have started to use technologies that can be more sensitive to radiation exposure in the inner magnetosphere. For example, as electronic components are minimized there exists the possible for a single high energy proton to disrupt an electronic circuit causing loss capability that could lead to complete and irreversible failure. One solution employed is to heavily shield these types of circuits. This strategy tends to add weight to a system, resulting in an increase of cost to the launch.

Present empirical models that are used in spacecraft design are inadequate in the specification of the radiation environment's full energy range as well as its extreme and average intensity conditions [5,6]. NASA has the standard electron and proton models know as AE-8 and AE-8 respectively. Each model exists for both solar minimum and maximum conditions. These are empirical models that were based on data taken from a number of satellites over several years [7]. Brautigam et al. [6] addressed short falls in the empirical models with the construction of a new model based on data from the AFRL's Combined Release and Radiation Effects Satellite (CRRES), which experience a very dynamic inner magnetosphere and measured higher energy particles.

The NASA models are compiled from data collected between 1958 and 1979. AP-8 has an energy range of 100 keV to 400MeV for protons, and AE-8 covers 40 keV to 4.5 MeV in the inner radiation belt and 40 keV to 7 MeV in the outer radiation belt. In contrast, the AFRL model covers 1MeV to 100MeV range for protons in MEO region and covers 0.5

MeV to 6.6MeV for electrons in both MEO and GEO regions. Radiation doses rates were calculated from the NASA and AFRL models [9, 10, 11] to compare the range of differences. The dose rates, as seen behind 0.23 inches of an Al shielding layer, was calculated using the AFRL's CRRES and NASA's AE-8 and AP-9 models, noting that NASA models were run under quiet solar conditions. Included in the calculation of the dose rates were electron of energies greater than 2.5 MeV and protons of energies greater than 135 MeV. The resulting dose rates are shown in Figure 6. As it can be seen, the dose rate calculated with the NASA AE-8 and AP-8 models in the slot region seriously under predicts that of the CRESS models. From the dose rate calculated from the NASA models, the number of years that it would take a spacecraft in a MEO orbit at 8000 km to be exposed to 100kRad would 88 years. Whereas, the number of years to reach 100kRad using the dose rate calculated from the CRESS Active model is only 1.1 years. This has a direct implication for the expected lifetime of a spacecraft. This difference of these models results has lead to an effort, which is well underway, to create new radiation specification models for electrons (AE-9) and protons (AP-9) [12, 13].

The space systems designed for the MEO region today are being built utilizing technology known to be susceptible to the effects of the harsh inner magnetospheric environment. The DSX SWx includes an effort to improve radiation specification models by providing data collected to the effort creating the new AE-9 and AP-9 models. These new models are expected to reduce the margin of error in the environment estimates that the spacecraft design requirements are based on. Thus, DSX SWx data will aid in reducing costly over-design of spacecraft operating in MEO. Also, accurate models of the space radiation environment are vital to the planning and operation of space missions in the inner magnetosphere.

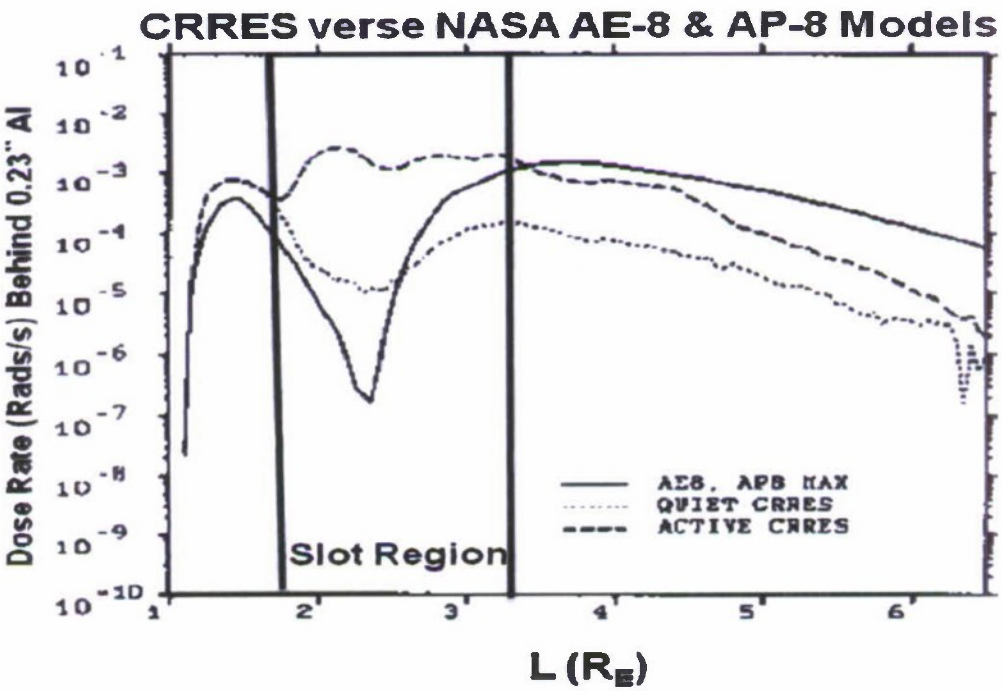


Fig 6. Comparing the standard model dose rates illustrates the uncertainty in radiation dose rate in MEO. The uncertainty forces spacecraft designers to increase shielding mass of electronics or accept an increase risk of damage to those electronics.

2.1 Low Energy Electrostatic Analyzer (LEESA)

The LEESA sensor was built, tested and calibrated by the Air Force Research Laboratory (AFRL) Battlespace Environment Division (RVB). The original design was made by Amptek Inc. of Bedford MA. This design was adapted and modified by AFRL/RVB for the current LEESA. LEESA is two sets of spherical electrostatic analyzers, one for electron and the other for ion measurements. The LEESA measures the energy fluxes and energy spectra for low energy electrons and protons ranging from 20eV to 50 KeV at 40 log-spaced steps. These low energy particles are responsible for surface electric charging and damage to thin films such as thin-film photovoltaic, conventional solar cell cover glasses, and coatings. The expected energy resolution for the LEESA is $\Delta E/E = 4.9\%$. There are two equally sized apertures; one for ion and one for electron measurements. Each LEESA aperture has a field of view of 120° x 15°, as shown in Figure 7a. LEESA also measures the directionality of the particles by offering multiple angular zones. There are 11 micro-channel arrays, which provide 5 angular zones and one background channel (see Figure 7b).

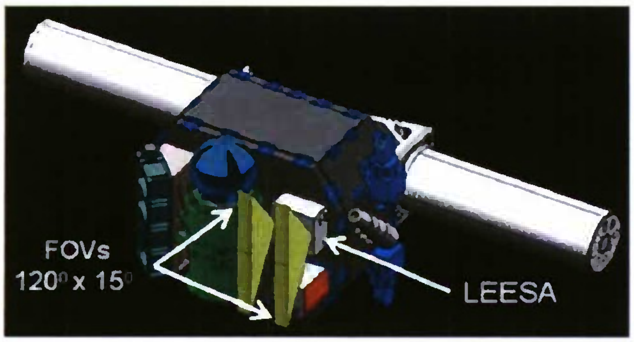
LEESA is comprised of two concentric quarter spherical sets, each having a small gap between them. This configuration of quarter spherical analyzers was chosen to increase sensitivity, minimize the size of the sensor and to exploit a compact layout. The inside spherical section has an attraction voltage and the outside section has the repelling voltage. The voltage difference between the two sections is step through the energy range. A charge particle with right energy will travel between the spheres sections (show in Figure 7b) and reach the detector plane.

LEESA is designed to operate at two different data rate levels. At the high data rate level the instrument will sample 80 voltage steps in one second or an 80Hz sampling rate. The low data rate of the sensor will sample 8 voltage steps in one second, or an 8Hz sampling rate. The LEESA dimensions are 116.84 x 212.73 x 209.550 mm and weighs 3.5 kg.

2.2 Low-Energy Imaging Particle Spectrometer (LIPS)

The LIPS is a scintillator-based sensor is designed to monitoring the lower energy charged particle environment for the expected energy range of protons and electrons in 6 energy bins (logarithmically spaced) for 20 KeV through 1MeV and has eight angular bins for angle of arrival measurements. This sensor was design, built, tested and calibrated by Physical Science Inc. (PSI) located in Andover, MA. This particle energy range is responsible for deep dielectric charging in electronic systems on spacecraft exposed to the inner magnetosphere.

(a)



(b)

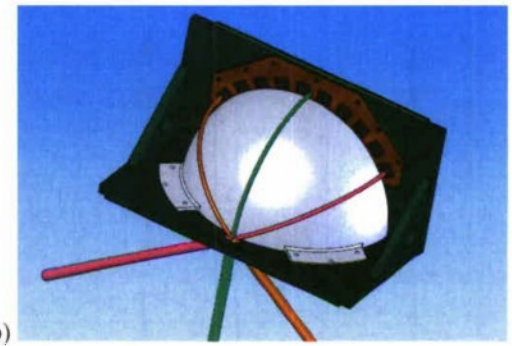
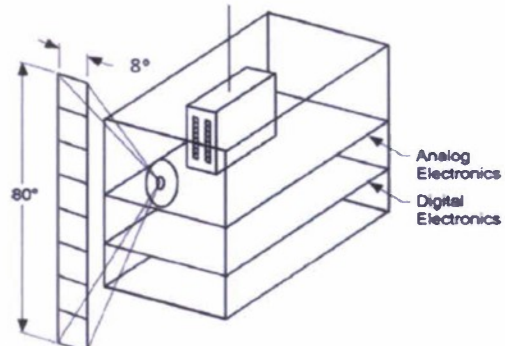
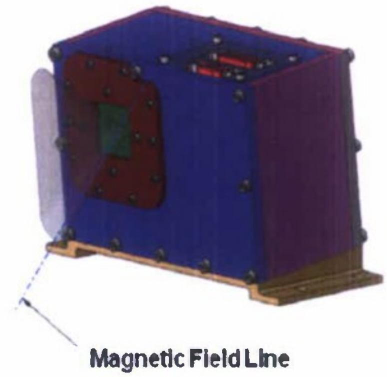


Fig 7. (a) Shown is the location of LEESA on the PM with it's the field of view. (b) LEESA, one of two electrostatic analyzers is shown, it has 11 micro-channel array provides 5 angular zones and one background channel (not seen in this view).

The LIPS does not rely on a magnetic sector to discriminate between electron and proton particles. LIPS use the advantage of the particle cross-section characteristics and scintillator properties to differentiate between electrons and protons [14]. Basically, the LIPS is configured as a "pinhole camera" type with particles entering the collimator aperture and incident on particle-specific scintillator focal planes (Figure 8a). The scintillator is designed specifically to respond only to either protons or electrons within a specific energy range. The scintillator is coupled directly to a multi-anode photomultiplier tube (PMT). Owing to their particle-specific response, the scintillator themselves provide the particle discrimination. The pulse amplitude defines the particle energy and the spatial position provides angular information. The LIPS uses a technique of overlaying a thin layer of polymer over a scintillator. For the case of protons, the total thickness of the scintillator is small and the electrons punch through without leaving energy in the scintillator. The protons stop in the scintillator and their energy can be measured. In the case of electrons, the polymer layer is thick enough to stop protons while the electrons deposit their energy in the scintillator. The LIPS has a nominal field of regard of 80° x 8°, which the edge of the field of view aligns with the earth magnetic field line when the DSX spacecraft is in its magnetic field line tracking mode[1] (shown in Figure 8b). The LIPS dimensions are 139 x 76 x 95 mm and weights 1.44 kg.



(a)



(b)

Fig. 8. (a) Shown is the field of view for the LIPS and the aperture "pinhole" configuration. (b) LIPS' edge of the field of view is intended to align with the magnetic field with DSX spacecraft is in its field line tracking mode.

2.3 Compact Environmental Anomaly Sensor (CEASE)

The CEASE [15] was originally designed and built by Amptek Inc. of Bedford MA. However for the DSX mission, a CEASE was reconditioned, tested and calibrated by Assurance Technology Corp. of Carlisle MA. CEASE is comprised of two dosimeters, and two particles detectors and is shown in Figure 9. There is also a solid-state Si detector telescope, consisting of two coaxially mounted sensors, capable of measuring integral and broad differential fluxes of electrons in the range of 0.06MeV to >2MeV and protons in the range from 1MeV to ~ 120MeV. The two CEASE independent dosimeter sensors are located behind aluminum planar shields, 0.20cm and 0.63cm thick, respectively, making particle flux measurements. The two thicknesses correspond to penetration energy thresholds of 20 and 35 MeV for protons, and 0.1.2 and 2.5 MeV for electrons [15].

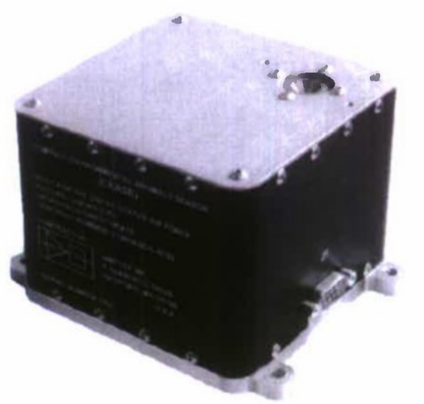


Fig. 9. Pictured is the Compact Environment Anomaly Sensor (CEASE).

The CEASE telescope has a 90° field of view and the two dosimeters both have an 180° field of view as shown in Figure 10. CEASE has flight heritage on the Department of Defense (DoD) Space Test Program (STP) Tri-Service Experiment-5 (TSX-5) spacecraft in an low earth orbit that was launch 2000 and had continuous operations for over six years [15,16,17]. The CEASE is a small and compact instrument with the dimensions of 85.34 x 101.6 x 12.0mm and has mass of 1.0 kg.

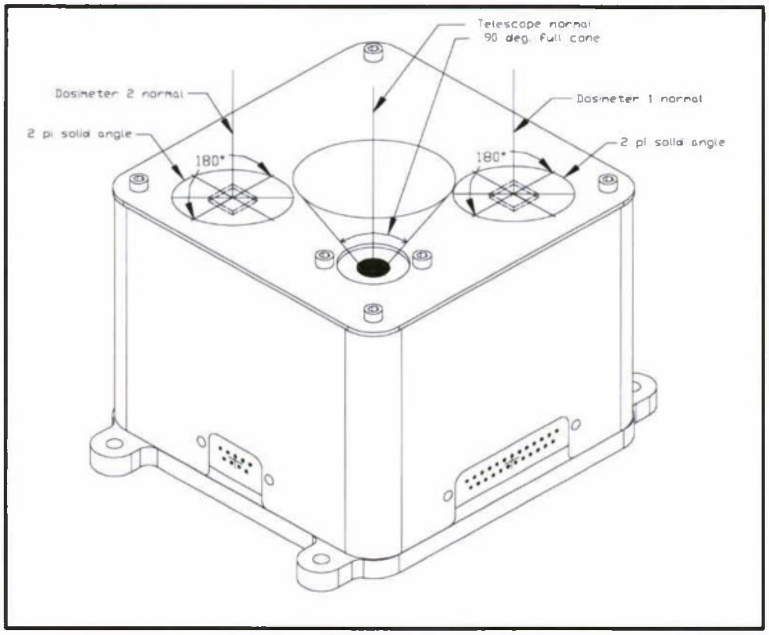


Fig.10. Shown is CEASE with the field of views of the two dosimeters and the particle telescope.

2.4 High-Energy Imaging Particle Spectrometer (HIPS)

HIPS is an innovative charged-particle spectrometer capable of measuring the flux and angular distribution of high-energy protons of the energy range of 30-300 MeV in 8 differential energy bins and electrons of the energy range of 1-30 MeV) also in 12 differential energy bins. HIPS measure the angle-of-arrival of both the protons and electrons in 8 angular bins. HIPS uses a combination of a silicon solid-state detector, a silicon solid-state strip detector, and a scintillator in it detection system. Due to instrument mass limitations and the particles' high energies, the path of charged particles through the spectrometer's detector cannot be controlled solely by material shielding. Registering only particles within the detector's acceptance cone is accomplished through a combination of metal collimator, anti-coincidence detectors, and detector signal processing logic. Measuring each particle's direction of arrival is done through a combination of the collimator's aperture, the segmented nature of the silicon strip detector, and detector signal processing logic. The HIPS has a nominal field of regard of 90° x 12.5°, which the edge of the field of view aligns with the earth magnetic field line when the DSX spacecraft is in its magnetic field line tracking mode[1] (shown in Figure 11). The HIPS dimensions are 200 x 142 x 191 mm and weights 4.6 kg.

Fig. 11. The HIPS sensor field of view aligns with the magnetic field line as shown.

2.5 High Energy Particle Spectrometer (HEPS)

The HEPS was originally designed and built by Amptek Inc. of Bedford MA. However for the DSX mission, HEPS was reconditioned, tested and calibrated by Assurance Technology Corp. of Carlisle MA. HEPS measures the differential energy spectrum of protons from 20 to 440 MeV, in twenty-two logarithmically spaced energy channels, and the integral flux for protons above 440 MeV. It has an angular resolution of 12^0 full cone. Although originally designed to measure protons, it also includes a number of data channels for measuring background events, and 20 channels for measuring electrons above ~1.5 MeV. The HEPS instrument consists of two separate modules as shown in Figure 12. The sensor module (left box) is electrically connected to the electronics module (right box) with an electrical cable and is mounted on the DSX spacecraft in a tower configuration (see Figure 4). The HEPS instrument is designed to measure the energy of a proton entering the stack of detectors through the front collimator. Its incident energy and incident angle will determine the depth to which it penetrates the stack of detectors.

Fig. 12. Photograph of HEPS sensor (left) and electronics (right) modules.

3. CONCLUSIONS

The Space Weather Experiment (SWx) as a part of the AFRL DSX space mission will provide fundamental data on the inner magnetosphere energetic particle populations. This valuable data will lead to further understanding of the basic space physics of the region and including the "slot region" which has been shown to be extremely dynamic. The data collected will also benefit the next generation radiation specification models for electrons (AE-8) and protons (AP-9) [12, 13] by providing both the angular and the energy distribution of protons and electrons in the inner magnetosphere.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contributions of numerous persons from the DSX Program Management Office (PMO) to this paper. The mission and experiment design, spacecraft architecture, and requirements are the results of many years of dedicated efforts on DSX PMO at AFRL, Space Vehicles Directorate. Much of the detailed payload and instrument descriptions were adapted from information originating in design reviews and other materials provided by Amptek Inc., Assurance Technology Corp., and Physical Sciences Inc. Specific content provided by others includes many images in this paper. Specifically the spacecraft stow and deployed images (Figures 2, 4and 7a) were provided by DSX PMO, Figure 1, 6, and 7b were provided by AFRL Space Vehicles Directorate, Battlespace Environment Division. The other sensor images and field of views were provided by the sensor manufactures and DSX PMO.

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