An Evaluation of Continued SAMPEX Data Collection to the Goals of the Living with a Star Geospace Program

Prepared by the LWS Geospace Project Office

Overview

The Living with a Start (LWS) Geospace Mission Definition Team (GMDT) identified a number of objectives for which low altitude energetic particle flux measurements are important. This document assesses the value of continued SAMPEX data collection for providing such measurements. We consider a number of factors, including the status of the SAMPEX spacecraft, orbit characteristics, instrumentation capabilities, and data availability to determine the relevance of continued SAMPEX observations to the specific objectives of the LWS/Geospace program. We also investigate the likely availability of similar data from other programs and compare mission capabilities.

If operations continue, SAMPEX can provide four significant contributions to LWS/Geospace science objectives:

- (1) continued relativistic electron observations over another solar cycle. This will provide needed statistics concerning extreme event occurrence patterns.

- (2) observations of radiation belt particle loss rates during the RBSP mission. This is a measurement highly recommended by the LWS Geospace Mission Definition Team (GMDT) but is not currently within the program's resources. To make these observations, the spacecraft would have to return to a spinning state and have a lifetime longer than nominal to continue operations through the period after the RBSP launch.

- (3) support for science studies in conjunction with forthcoming missions, e.g., research isolating the effects of energetic particle precipitation on ionospheric electron density profiles.

- (4) observations to characterize variations of inner belt protons over the solar cycle and the relationship between the flux of energetic ions seen at low altitudes and Solar Energetic Particle events.

For these reasons, the LWS/Geospace Program strongly endorses continued operation, data processing, archiving, and analysis activities for SAMPEX with an ultimate goal of attaining overlap with forthcoming LWS/Geospace missions. This endorsement is predicated on (1) SAMPEX returning to a spinning state, and (2) NASA's acceptance and subsequent execution of the recently submitted SAMPEX data archiving plan. However, it must also be noted that within current budget guidelines the LWS/Geospace Program does not currently possess the financial resources to support SAMPEX operations, data processing, data archiving or data analysis without imposing further delays to the Geospace flight missions. Further delays to the LWS Geospace flight elements constitute an unacceptable risk to the scientific success of the program.

SAMPEX Observations

The Solar, Anomalous, and Magnetospheric Particle Explorer SAMPEX was launched in July 1992 into a 550 x 675 km altitude orbit with an inclination of 82°. During a 1-year prime mission phase and 10 years of extended operations, the SAMPEX team made numerous contributions to our understanding of the energetic particle environment in the vicinity of Earth, in particular the ionization states, energy spectra, and isotopic composition of galactic rays, anomalous cosmic rays, and solar energetic particle events, the acceleration mechanisms for relativistic magnetospheric electrons and protons, and the effects of precipitating electrons on middle atmospheric NOy. Although the Office of Space Science Senior Review held in 2003 recommended that SAMPEX science and instrument operations terminate in 2004, NASA will continue to track the spacecraft as part of an engineering test.

SAMPEX has been an integral component of the Sun-Earth Connection (SEC) fleet of spacecraft. With its 90-minute orbital period and high inclination, SAMPEX cuts across all L-shells four times per orbit at two local times, enabling the spacecraft to sample radiation belt precipitation from all magnetospheric L-shells. After completing more than one-half of a 22-year solar cycle, all instruments on the spacecraft still operate today. In particular, no problems have been noted with the instruments that measure energetic electrons. The spacecraft power supply is more than adequate: current solar array output is 240 W, while the load is 70 W. The SAMPEX mission is limited only by funding considerations and its expected reentry into the atmosphere, the date of which depends on high-altitude atmospheric density variations that will eventually produce a critical level of drag on the spacecraft. Current estimates for the mission lifetime place the re-entry dates anywhere from December 2010 to sometime after 2014, with nominal reentry in December 2011 (see Figure 1).

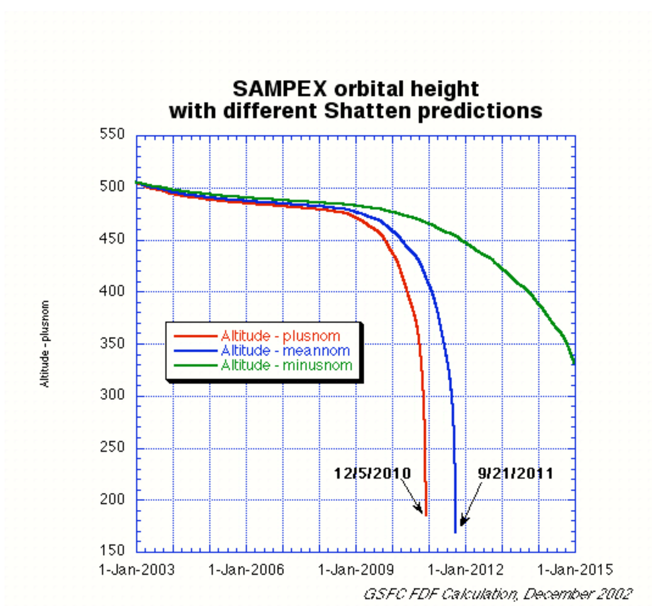


Figure 1. Predictions for SAMPEX reentry into the atmosphere. Results for high, nominal, and low Shatten drag models are shown.

Servers at the University of Maryland and the NSSDC currently provide limited portions of the SAMPEX data sets and plots (http://surya.umd.edu/www/sampex.html). The SAMPEX team has submitted a proposal to NASA to provide a much broader range of SAMPEX observations via the ACE mission data server at Caltech.

Table 1 lists the four SAMPEX instruments. Because it does not measure the energetic electrons of greatest interest to the LWS Geospace program, MAST will not be discussed here. The Low Energy Ion Composition Analyzer (LICA) is a time of flight ion mass spectrometer with a 17°x21° field of view. Singles rates from the front MCPs provide 1-sec time resolution observations of electrons with energies typical of the auroral ovals. Within the next year, these plates will begin to degrade and sensitivity will be lost. However, singles rates from the back MCPs provide 1-sec time resolution observations of the integral flux of electrons with energies greater than >500 keV.

Table 1. SAMPEX Instruments

Instrument/PI	Observation	Energy Range
HILT/Klecker	Ions	4 < E < 250 MeV/nucleon
	Electrons	>1 MeV
PET/Mewaldt	Protons	18 < E < 250 MeV/nucleon
	Helium	18 < E < 350 MeV/nucleon
	Electrons	2-6, 6-14, and 10-20 MeV
LICA/Mason	Ions	0.5 < E < 5 MeV/nucleon
	Electrons	>25, >500 keV (1s singles rates)
MAST /Mewaldt	Ions	10 < E < several hundred MeV/nucleon

The Heavy Ion Large Area Proportional Counter Telescope (HILT) is composed of a front ion chamber and two proportional counters filled with isobutene, followed by an array of 16 silicon solid state detectors in four rows, followed by a large proportional counter. The telescope was designed to measure 4 to 250 MeV/nucleon ions, the integral flux of electrons with energies greater than 150 keV, and the integral flux of electrons with energies greater than 1 MeV. The low energy channel electron capabilities were lost when the isobutene supply expired after the first year of operations. The instrument saturates during intense events.

The Proton/Electron Telescope (PET) is a solid-state telescope with multiple layers of solid state detectors. Electrons are measured using coincidences between the top elements of the telescope. In principle there are four electron channels: an integral channel > 0.4 MeV, and energy bands of approximately 2-6 MeV, 6-14 MeV, and 10-20 MeV. Although the instrument was designed to measure the energy spectrum from 1 to 30 MeV, we do not find such spectra presented in the scientific literature. Instead, observations from 3 channels within the energy range from 0.4 to 6 MeV are currently available on-line. PET has no angular measurement capabilities. Its field of view depends upon which elements of the telescope are being used, usually giving 58°, narrowing to 35° at the higher energies. Thus it usually measures precipitating particles in the non-spinning mode of operations.

To determine the loss rates of particles from the magnetosphere into the ionosphere, information concerning pitch angle distributions is essential. During the normal non-spinning mode of operations, the HILT observations can be used to determine whether the loss cone is filled, an indication of strong pitch angle scattering in the magnetosphere. Over the polar region, the magnetic field can make an angle of up to 30° with zenith. One row of HILT detectors looks closer to the edge of the loss cone than the other rows, providing crude pitch angle information. In practice, electron scattering in the HILT entrance windows and the front ionization chamber increases uncertainty by smearing the angular measurements.

Significantly better pitch angle coverage could be obtained from the LICA, HILT, and PET instruments by spinning the spacecraft. SAMPEX operated in a spinning mode (1 revolution per minute) for extended periods in 1996 through 1998, and briefly in 1999. The procedure for changing the spin state is onboard the spacecraft, and the transition to full spin up takes a couple of hours. This can be done at any time. Spinning the spacecraft has not previously caused any difficulties with signal reception. In spinning mode, the spin axis points sunward, and the instrument field-of-views look perpendicular to the spin axis. Consequently, the instruments obtain good pitch angle coverage at equatorial latitudes, less at higher latitudes. The basic sampling rate is 6s, giving 10 readings per spin. Papers using data from the spinning spacecraft have been published by Mazur et al. [GRL, 25, 849, 1998] and Greenspan et al. [JGR, 104, 19911, 1999]. Figure 2 shows an example.

Plots of SAMPEX data are currently available from a server at the University of Maryland (surya.umd.edu/www/sampex.html). A server at the NSSDC provides four categories of digital data: (1) 30-sec fluxes from several energy channels from each instrument (including electrons 1-6 and 3-16 MeV); (2) Polar cap averaged fluxes during each polar pass from the same channels that populate (1), (3) 30-sec rates from all channels of each instrument (including PET electrons from 4-15 MeV, 2-6 MeV, and 4-30 MeV); and (4) Polar cap averaged rates from numerous channels during each polar pass. A proposal to NASA, entitled "The SAMPEX Data Archive and User Interface for the SEC Community" and dated March 15, 2004, describes a plan to serve a wider range of observations and full documentation from the ACE science data center at Caltech, as well as reformat the observations for eventual submission to the NSSDC. If the proposal were approved and funded at the requested cost of $0.62M over a 3-year period, 6s intensities and count rates, high resolution count rates, polar cap flux averages, plots, and longer term averages would become available (including electrons 2-6, 6-14, and 10-20 MeV). Observations with 1-sec time resolution are available from the LICA detectors and would help immensely in determined particle pitch angle distributions, but are not listed in the data files to be delivered to the SAMPEX data archive.

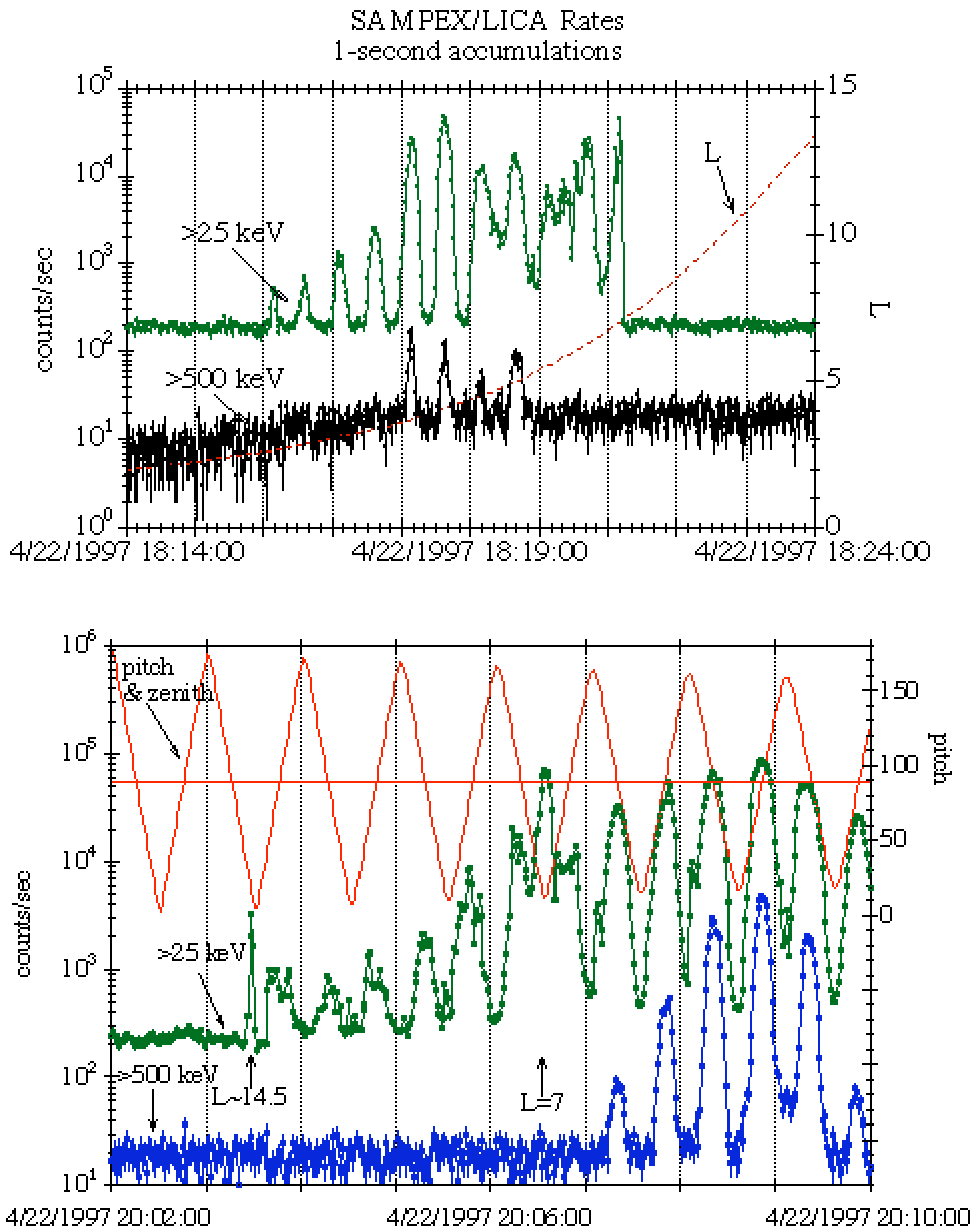


Figure 2. Count rates from LICA's back MCP offer excellent pitch angle coverage when the spacecraft is in spinning mode.

Comparison with Observations by Other Low-Altitude Spacecraft

From an LWS/Geospace program perspective, the main role of SAMPEX lies in its ability to observe particle loss from the radiation belts via precipitation. Thus the need for SAMPEX observations must be viewed from within the context of other operating or planned low-altitude spacecraft. NASA's Upper Atmosphere Research Spacecraft (UARS) was launched in 1991. With an orbital inclination of 57°, the spacecraft generally monitors the inner magnetosphere. The Medium-(MEPS) and High-(HEPS) Energy Particle Spectrometers of the Particle Environment Monitor (PEM) on UARS continue to observe energetic electrons and protons. MEPS provides spectra for both species over the energy range from 1 eV to 32 keV, while HEPS provides information concerning pitch angles distributions and energy spectra for protons with energies from 0.1 to 160 MeV and electrons with energies from 0.03 to 5 MeV. Because its energy resolution is ~100 keV, HEPS can provide observations of the electron spectrum with more resolution than SAMPEX. Furthermore, because HEPS consists of 6 telescopes mounted over a wide range of orientations relative to the zenith, the instrument provides the information needed to identify intervals of strong pitch angle scattering. Both MEPS and HEPS are functioning well, but the spacecraft has lost recording capability and batteries. Consequently, the instruments can only be activated during daylight when the solar array provides enough power, and the observations can only be received in real-time via TDRSS. Although the spacecraft will not reenter the Earth's atmosphere for at least 20 years even without orbit boosts, operations are expected to continue only until September 2005 to enable overlap with EOS Aura.

Existing NOAA Polar Orbiting Spacecraft (POES) and European Meteorological (METOP) spacecraft do not make observations of electrons at the energies of interest, only integral observations of energetic electrons with energies greater than 300 keV. NOAA, the Air Force, and NASA's Code Y are currently designing the National Polar-orbiting Operational Environmental Satellite System (NPOESS) series for initial launch in 2009. NPOESS will replace the POES series of spacecraft during the time frame of the RBSP mission. It is likely, although not certain, that each of the three simultaneously operating NPOESS spacecraft will carry a Medium Energy Charged Particle instrument in separate local time sun-synchronous orbits. The engineering specifications called for separate mirroring and precipitating electron measurements within at least 5 energy bands between 30 keV and 5 MeV, a wider range than SAMPEX. The two highest energy channels would measure electrons with energies from 0.65 to 2 MeV and 2 MeV to 5 MeV, no better than SAMPEX. The separate pitch angle measurements will permit identification of intervals or regions of strong pitch angle scattering, but not determination of full pitch angle distributions. A CEASE II instrument is under consideration for two NPOESS spacecraft. CEASE II consists of an electrostatic analyzer capable of measuring electrons and ions with energies from 5 to 55 keV in 39 bins and a solid-state telescope capable of measuring electrons from 40 keV to ~4 MeV.

Global Positioning Spacecraft (GPS) launched into 20,000 km radius orbits since February 2000 will carry CXD detectors from LANL that are capable of measuring omnidirectional energetic electron fluxes in 11 channels covering the energy range from 0.14 to 6 MeV. Observations from up to 9 spacecraft may be available at any given time. The spacecraft will provide observations of the energetic particle environment within the range of L shells from 4 to 10. These observations will be useful in determining spatial and temporal variations of the radiation belts, but they will provide no useful information concerning particle loss.

To summarize, both UARS and NPOESS could provide energetic electron observations over a range of energies less than or comparable to that for SAMPEX with crude information concerning pitch angle distributions. However, UARS operations will terminate in about one year, while NPOESS will no make observations before 2009. Neither spacecraft provides better pitch angle coverage than SAMPEX in a spinning state. Omnidirectional flux observations from the GPS spacecraft will not provide the pitch angle coverage needed to address Geospace objectives.

Finally, it should be noted that NASA does not have guaranteed access to observations from non-NASA spacecraft. For example, although NOAA's National Geophysical Data Center will be the designated provider of NPOESS space environment observations, NOAA has not allocated the funds needed to verify the observations or make them available.

Advantages of Continued SAMPEX Operations

If operations continue and SAMPEX returns to a spinning state, the spacecraft will make four significant contributions to LWS/Geospace science objectives:

- (1) continued energetic particle observations over another solar cycle. This will provide needed statistics concerning extreme event occurrence patterns.

- (2) observations of radiation belt particle loss rates during the RBSP mission. This is a measurement highly recommended by the LWS Geospace Mission Definition Team (GMDT) but is not currently within the program's resources. To make these observations, the spacecraft would have to return to a spinning state and continue operations through the period after the RBSP launch.

- (3) support for science studies in conjunction with forthcoming missions, e.g., research isolating the effects of energetic particle precipitation in GPS-derived ionospheric electron density profiles.

- (4) observations to characterize variations of inner belt protons over the solar cycle and the relationship between the flux of energetic ions seen at low altitudes and Solar Energetic Particle events.

We consider each of these in turn.

Continued observations of extreme energetic electron events within the magnetosphere

Although rare, extreme energetic particle events can be lethal. They have been implicated in numerous recent satellite anomalies. Figure 3 illustrates SAMPEX energetic electron observations from a geomagnetically disturbed period in late 2003. Determining the relationship, if any, between energetic electron flux enhancements and spacecraft anomalies is a topic for ongoing scientific investigation. Continued SAMPEX operation will enable researchers to determine the magnetospheric response to space weather events observed by SOHO or SDO using NASA assets.

Because they are rare, occurrence patterns for extreme events are poorly understood. Better statistics will help identify the solar wind and magnetospheric conditions causing these flux enhancements, the peak flux levels attained, the range of radial distances over which they occur, the rate at which particles precipitate, and the energy input into the ionosphere and thermosphere. In conjunction with magnetospheric observations (e.g. by energetic particle instruments on Polar), continued SAMPEX observations will provide the statistics needed to derive the occurrence patterns for these events as a function of varying solar and solar wind disturbances, such as high speed streams, coronal mass ejections, and solar energetic particle events. For example, there have been reports that SAMPEX observations of energetic electron flux levels track those in the magnetosphere very well, with the low altitude flux levels being 10% those in the magnetosphere except during the main phase of geomagnetic storms [Blake et al., LWS Session, Fall AGU, 2003]. These reports need to be verified by further scientific study, in particular study investigating the pitch angle distributions of the particles seen by Polar and SAMPEX. Note that due to Polar's high apogee and long orbital period, the spacecraft cannot provide high cadence surveys of the radiation belts. Within the array of existing and forthcoming NASA spacecraft, this is a role that only SAMPEX can fulfill.

SAMPEX observations can also play a vital role in case studies of selected extreme events. During the recent November 2003 space weather event, SAMPEX observed an intense injection of energetic magnetospheric electrons into the slot region at L ~ 2-3 (see Figure 3), resulting in the greatest intensity of trapped ions and electrons observed in this region over the 12-year SAMPEX mission. However, despite the fact that a large solar energetic particle (SEP) was in progress, few if any SEP ions entered the slot region. This is in marked contrast to the case for two November 2001 events. The reasons for the varying response are currently under investigation.

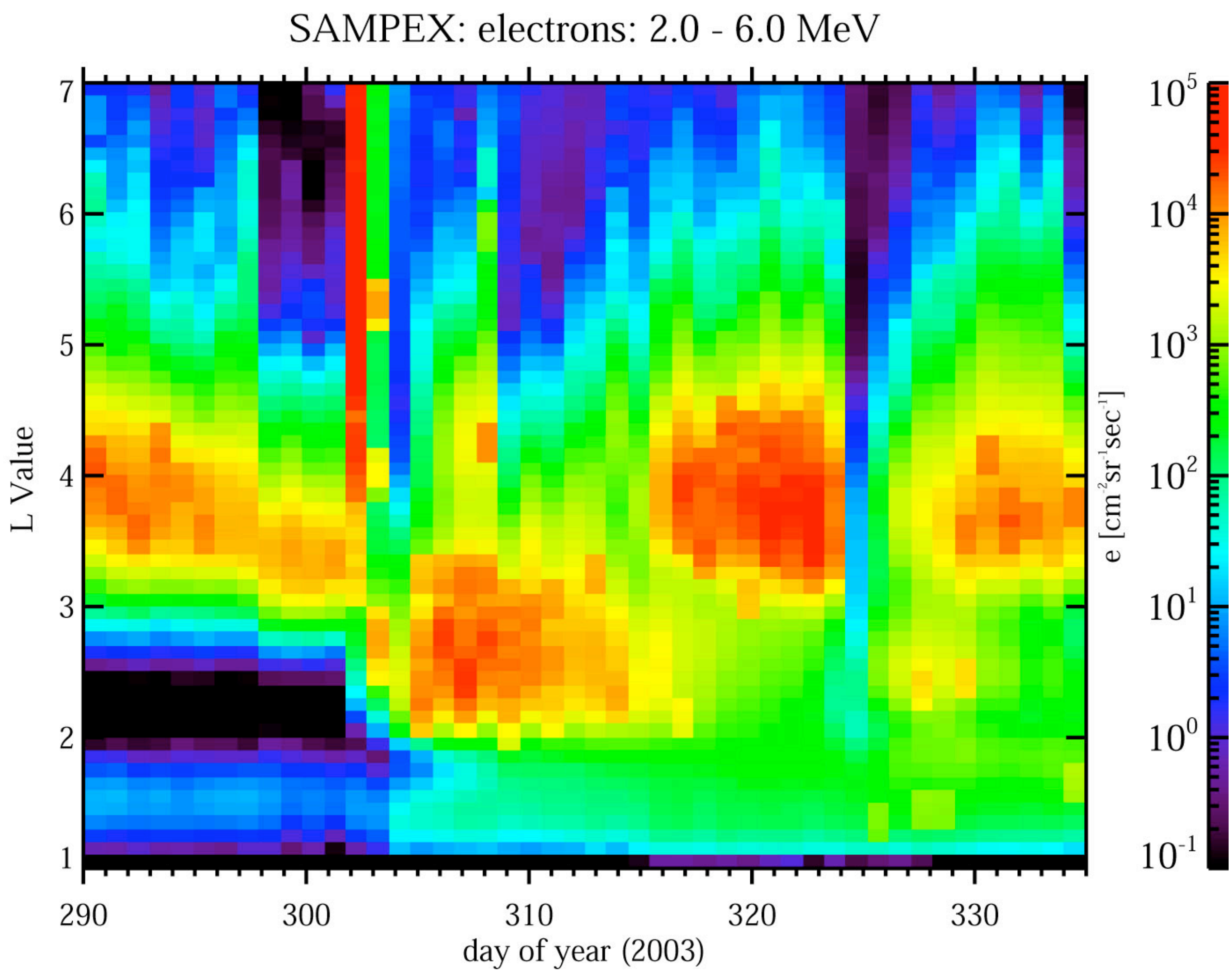


Figure 3. SAMPEX monitors variations in the radiation belts.

Observations of radiation belt particle loss during the RBSP mission.

The greatest benefits from continued SAMPEX operation will be derived if SAMPEX operates beyond the launch of the LWS Radiation Belt Storm Probes (RBSP). One of the key objectives of the Geospace missions, as identified by the GMDT, is to differentiate amongst competing processes causing the precipitation and loss of outer belt energetic electrons. While the RBSP will make in situ observations of energetic electrons within the outer belt, there are currently no plans for any asset within the Geospace program to make observations of the corresponding precipitating particles. As discussed above, the NPOESS spacecraft will provide observations of energetic electrons during the time period of interest, but not with the necessary pitch angle coverage. If SAMPEX continues to operate for the next decade, it will be possible to correlate SAMPEX observations of particle precipitation at low altitudes with RBSP observations of the parent population and waves in the magnetosphere. If SAMPEX enters a spinning state, SAMPEX pitch angle distributions will help discriminate between proposed mechanisms for particle loss from the magnetosphere. In particular, it will be possible to distinguish between models for strong and weak energetic particle pitch angle diffusion into the loss cone. Results would be limited to the energy range covered by SAMPEX observations.

Support for science studies in conjunction with forthcoming missions.

One of the key objectives of the LWS/Geospace program is to characterize the spatial and temporal variations of ionospheric density and chemistry during the course of geomagnetic storms. Precipitating relativistic electrons ($E > 1$ MeV) can penetrate below 60 km into the D-region, enhancing ionization and drastically impacting middle atmosphere and ionospheric chemistry. Figure 4 illustrates the heights in the atmosphere where the particles measured by the different instruments on SAMPEX cause the greatest ionization.

New methods to relate ionospheric density profiles to SAMPEX observations of precipitating electrons are currently underway. The density profiles can be visualized using the recently available global positioning satellite (GPS) occultation methods. When the line of sight from a low-Earth orbiting satellite to a GPS satellite passes through the Earth's limb, ionospheric remote sensing of electron densities becomes possible. The phase and amplitude of GPS signals are affected by changes in the index of refraction as they pass through the ionosphere. Using Abel inversion techniques and assuming spherical geometry, these occultation measurements can be converted into electron density profiles. SAMPEX observations of precipitating electrons and Air Force Space Test Program IOX (launched September 29, 2001) GPS observations have been examined to identify possible effects of the precipitating electrons on D-layer ionospheric densities (see Figure 5). Similar studies are planned using Air Force CORISS (to be launched on C/NOFS December 2004). The primary goal of these occultation experiments is to improve operational models for ionospheric and thermospheric forecasts [Lorentzen et al., Fall AGU, 2002]. Future work will require comparison with simulations of the occultation retrieval process and D-region ionization, both currently underway and funded by a LWS grant to Paul Straus at Aerospace Corporation.

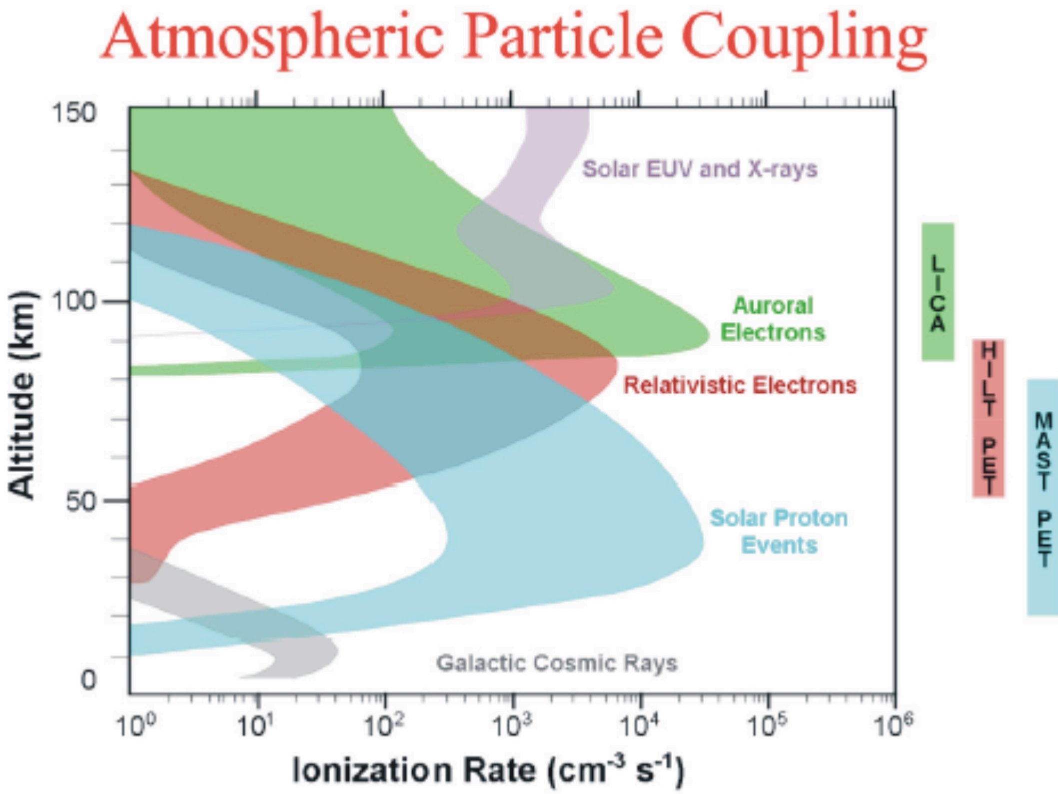
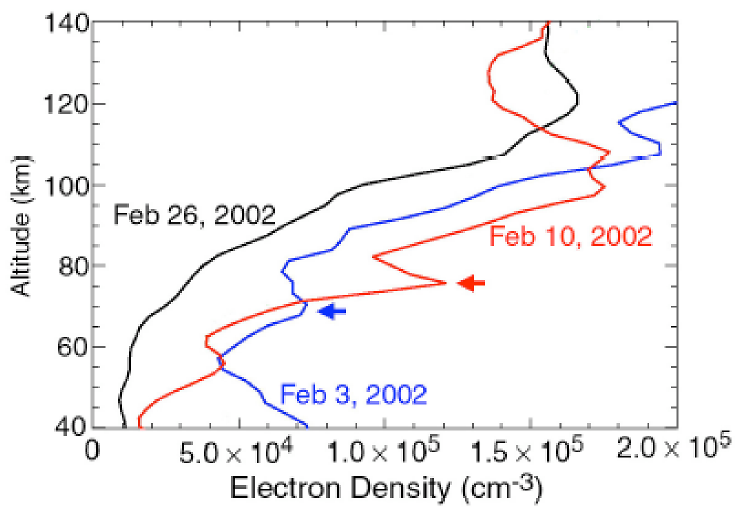


Figure 4. Ionization rates of photons and energetic particles as a function of height in the atmosphere showing the range of values for different events. Bars on the right hand side show the energy coverage and corresponding atmospheric depth of particles measured by SAMPEX instruments for electrons (green, pink bars) and protons + He (light blue bar).



Three electron density profiles derived from GPS occultation measurements. *Arrows* mark distinct peaks near 70 km altitude on Feb. 3 and 10.

Figure 5. Low altitude portions of three IOX electron density profiles derived from GPS occultation measurements using the Abel inversion technique. The data were acquired between 4 $\leq$ L $\leq$ 6 in the southern hemisphere during February 2002. All three profiles exhibit density peaks in the E-region between 100 and 120 km. In addition, the profiles on Feb. 3 and Feb. 10 show density peaks at lower, D-region altitudes. These D-region peaks were accompanied by increases in the >1 MeV electron intensities detected by SAMPEX in the region between L~4-6.

Continued observations of ions in a variety of regions over another solar cycle.

While the low altitude electron measurements from SAMPEX would help fulfill the highest priority science objectives of the RBSP mission, continued ion observations would provide unique data for the long-term characterization of lower priority objectives. SAMPEX would thereby acquire full solar cycle measurements of the intensity and energy spectra of the inner belt particle population for developing and validating physics-based and specification models of inner belt protons over solar cycle time scales. SAMPEX would also provide key data to determine the quantitative relationship between very energetic ion fluxes in the interplanetary medium and their fluxes at low altitudes, particularly the geomagnetic cutoffs as a function of solar and geomagnetic activity.

Recommendation of the LWS/Geospace Program

Continued SAMPEX operations in a spinning state will address Geospace objectives by:

- (1) continued energetic particle observations over another solar cycle. This will provide needed statistics concerning extreme event occurrence patterns.

- (2) observations of radiation belt particle loss rates during the RBSP mission. This is a measurement highly recommended by the LWS Geospace Mission Definition Team (GMDT) but is not currently within the program's resources. To make these observations, the spacecraft would have to return to a spinning state and continue operations through the period after the RBSP launch.

- (3) support for science studies in conjunction with forthcoming missions, e.g., research isolating the effects of energetic particle precipitation in GPS-derived ionospheric electron density profiles.

- (4) observations to characterize variations of inner belt protons over the solar cycle and the relationship between the flux of energetic ions seen at low altitudes and Solar Energetic Particle events.

No existing or planned low-altitude mission will make the energetic particle observations needed to fulfill all the objectives of the LWS/Geospace program. However, when viewed from within the context of all known existing and planned low-altitude missions, SAMPEX has the capability to make the most significant contributions to these objectives. Consequently, the LWS/Geospace Program strongly endorses continued operation, data processing, archiving, and analysis activities for SAMPEX, with the ultimate goal of reaching a period of overlap with the LWS/Geospace missions.

Nevertheless, it must be noted that the LWS/Geospace Program does not currently have the financial resources to support the recommended SAMPEX operations, data processing, data archiving or data analysis without imposing delays to the LWS/Geospace flight missions. Further delays will irreparably harm the science goals of the Geospace missions and therefore diversion of LWS/Geospace funds for this purpose is considered to be an unacceptable risk.