Ballistic Dynamics of a Relativistic Electron Beam for Mapping of the Magnetosphere

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Introduction

Relativistic electrons fired from an orbiting satellite will propagate along the field lines of the magnetosphere and can impact the Earth's atmosphere to produce a signal detectable by ground stations[1]. **Such a diagnostic would enable direct validation of magnetospheric models, assist in answering outstanding questions on auroral arcs, and contribute to space weather prediction tools**. We examined the loss cone of a simulated relativistic electron beam for several injection points within the Earth's magnetosphere during the stages of a prominent geomagnetic storm event, selected the ideal launch point, and determined the beam impact location, intensity, and spread for the various stages of the disturbance. **This verified that a satellite mounted electron gun can create unique, observable ground signals, which differ depending on the current storm phase and injection position.**

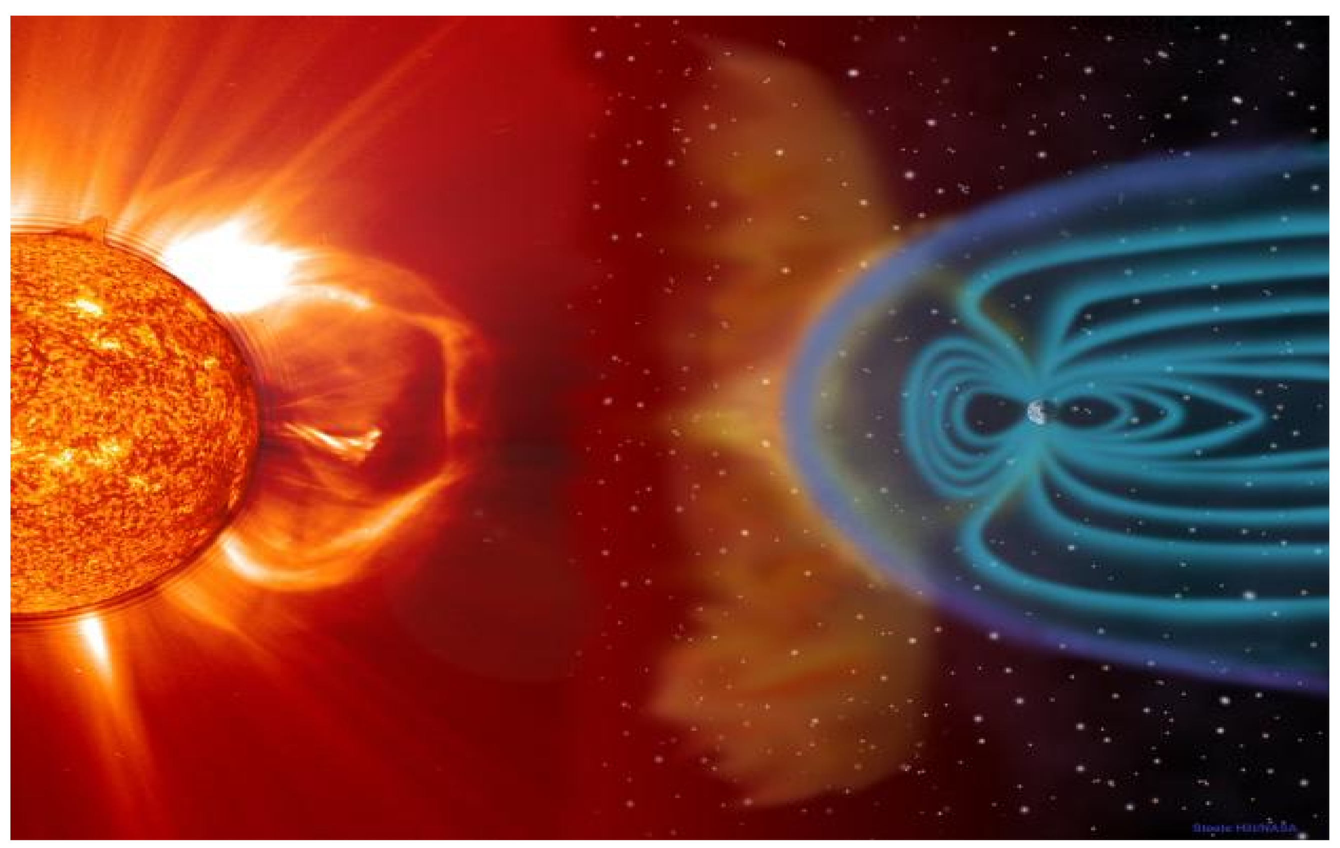


Fig. 1 Conceptualization of a coronal mass ejection impacting the Earth's magnetosphere. Courtesy of NASA & ESA SOHO/LASCO/EIT

Magnetic Field Model

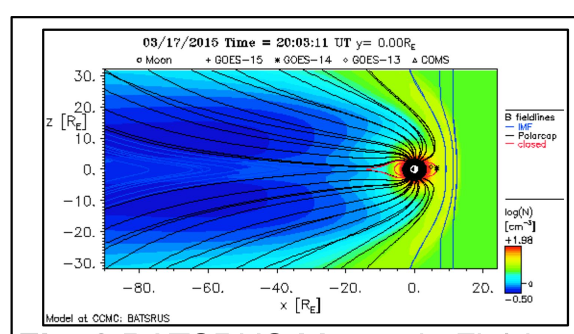


Fig. 2 BATSRUS Magnetic Field Visualization in Meridian Plane[2]

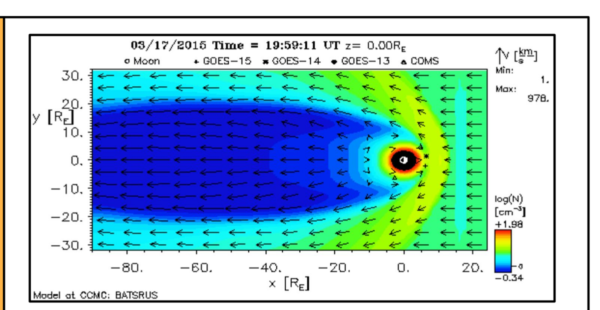


Fig. 3 BASTRUS Magnetic Field Visualization in Plane of Earth's Orbit[2]

Magnetic field data used to simulate particle trajectories and beam dynamics came from the BATSRUS model, a tool hosted by NASA and calibrated with observational satellite data to provide realistic space weather analysis support. **Each injection time simulated had a corresponding unique BATSRUS field.**

Beam Parameters

The simulated electron gun in this study had a designed energy of 1 MeV±2%, with an emittance of 10^{-4} cm-rad. 1000 particles were simulated in each beam trajectory, and the beam was fired from the $(-5,0,0)R_{\oplus}$ position in geocentric coordinates for seven different times corresponding to the various phases of a major geomagnetic storm event. For each injection, the beam was simulated with two pulses of 500 particles and 1000 pulses of 1 particle.

Loss Cone Analysis

For relativistic electrons, injecting a beam parallel to a field line connected to Earth is not a guarantee that the particles will impact the Earth[1]. To determine which angles relative to the local field lines at the injection point would result in the particles being "lost" rather than being mirrored by Earth's dipolar magnetic field, a statistical sampling method was adopted. One particle was injected for each coordinate over a grid of azimuthal and altitudinal angles (λ and δ) relative to the local field lines, and a particle pusher code using the Boris algorithm[3] and local magnetic field data from the BATSRUS model was used to determine whether or not the particle was deposited in the atmosphere of the Northern Hemisphere, where observations would take place. **For this method, 1200 particles were sampled in 45 different location and time combinations and the resulting loss cone, if it existed, was mapped.** Selected loss cones were used to determine which angles to fire at for the full beam simulations at different times during the geomagnetic storm event.

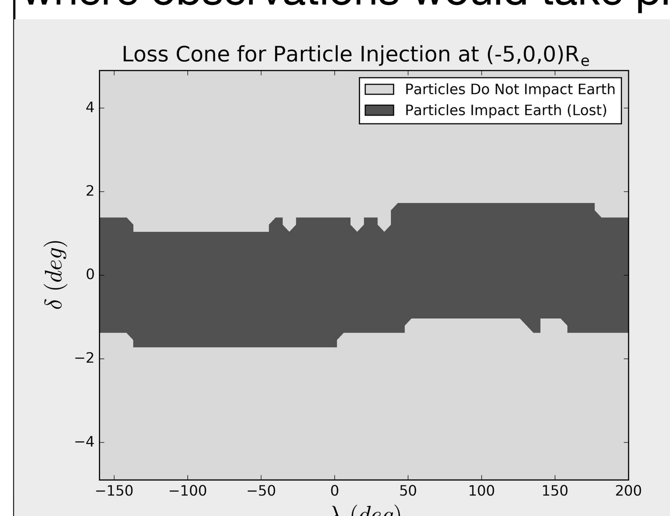


Fig. 3 Loss Cone for Particles injected on March 18th 2015 at 19:20 UTC

Beam Impacts

After considering the loss cone data, the optimal launch point across all storm phases was selected and full beams were simulated to determine the number of particles deposited in the topside atmosphere, the spread of the beam, and the latitude and longitude of each impacted particle. The two pulse beam simulations had an over 90% impact rate in all cases except the final storm recovery phase. The beam footprint could be approximated as a circle, with a typical radius ~40 m. For the 1000 pulse beam, there were similar impact rates, however the motion of the satellite as it fired became apparent in the elongated pattern of the footprints, which could be approximated as ellipses with typical major axes ~65 m.

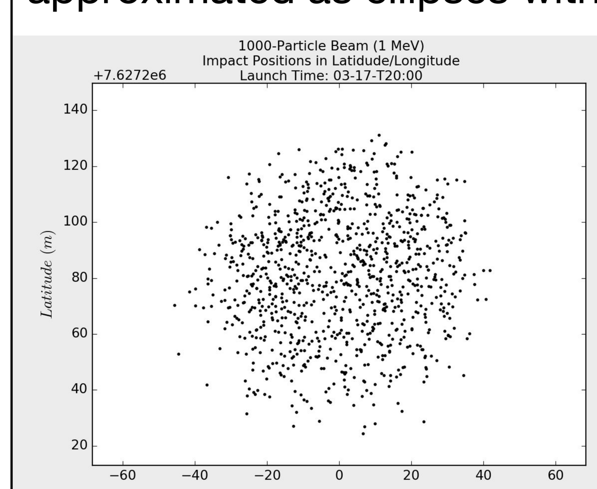


Fig. 4 Impacted particle locations for a two pulse beam at 20:00 UTC on 03-17-2015, plotted in absolute latitude and relative longitude

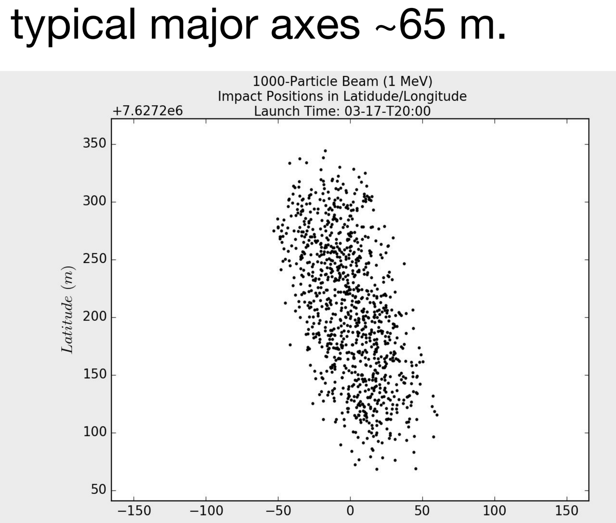


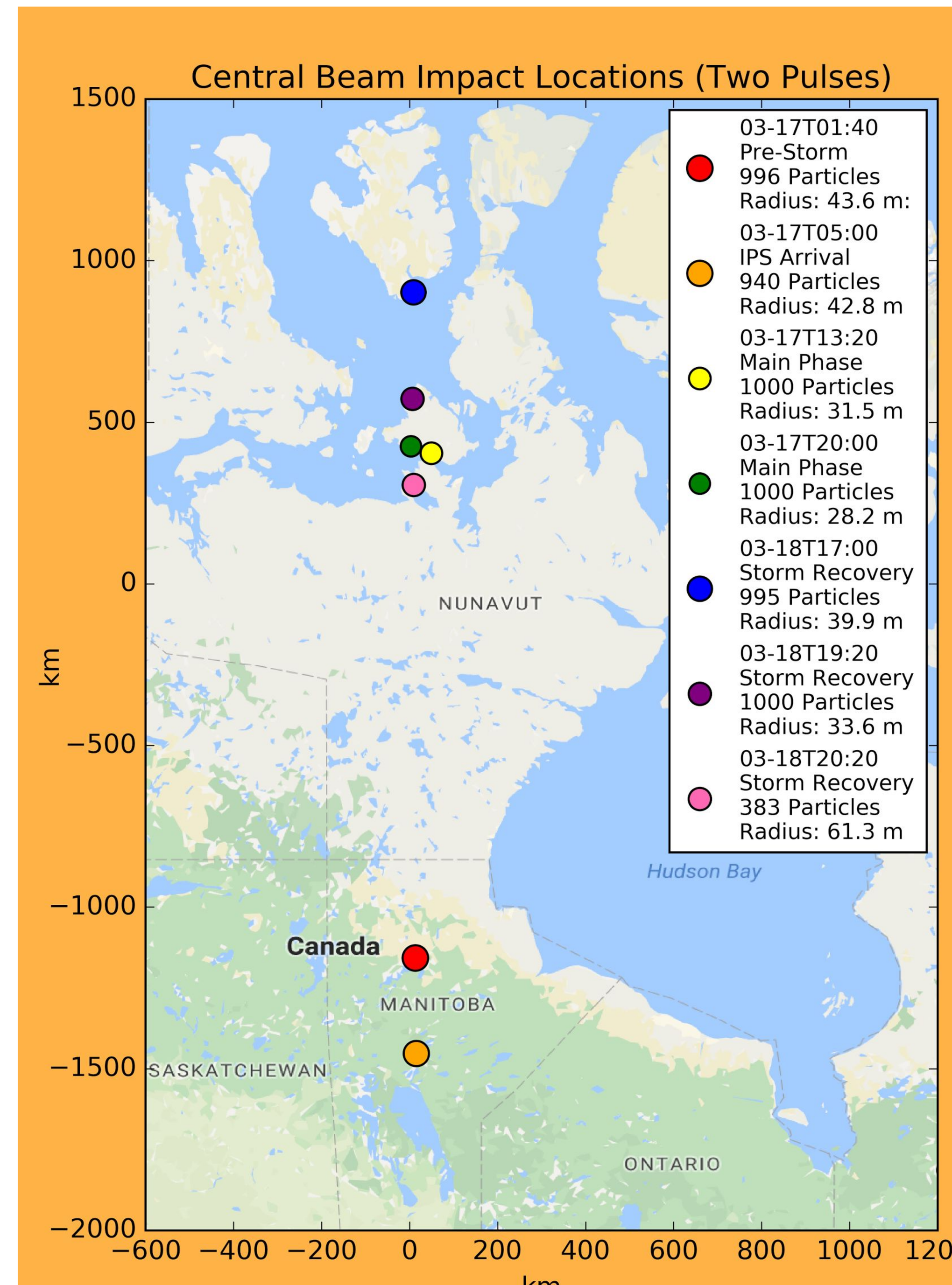
Fig. 5 Impacted particle locations for a 1000 pulse beam at 20:00 UTC on 03-17-2015, plotted in absolute latitude and relative longitude

Signal Size and Location

Once the final locations were determined for each of the deposited particles, the beam spot information was examined in a global context. **Figures 6 & 7 display the final beam footprints on the Earth for the two types of beam simulated, two pulses and 1000 pulses.** Each point represents the beam fired at a different time in the storm event beginning on 03-17-2015, from one common launch point. Information on the time of injection, storm phase, number of particles impacted, and spot size is included. The final latitudes are true latitudes relative to the Earth with its rotation axis aligned with the Z direction in geocentric coordinates, but in reality would vary from the plotted latitudes by up to ± 23.5 degrees depending upon the time of year that the particles are launched. Additionally, the longitudes are plotted relative to each other, while in a true use of this beam setup the longitudes would be spread around the planet as the Earth rotated throughout the course of the days of the solar storm event. The key demonstration with these plots is that **particles fired from the same injection point will impact at measurably different locations on the Earth due to differences in the distortion of Earth's magnetic field through various geomagnetic storm phases**. Furthermore, each beam will deposit most of its energy within a small enough region to be detectable by ground stations.

Conclusion

A satellite mounted electron gun capable of firing a beam to impact the Earth's atmosphere and create signals observable from the ground will produce data usable for mapping the magnetosphere. This will help to confirm current magnetospheric models capable of predicting geomagnetic disruptions with an increased accuracy crucial to the protection of satellite assets that can be damaged or destroyed by solar storm events. **This analysis proves, with the most detailed data currently available, that this type of satellite could produce the necessary atmospheric signatures.**



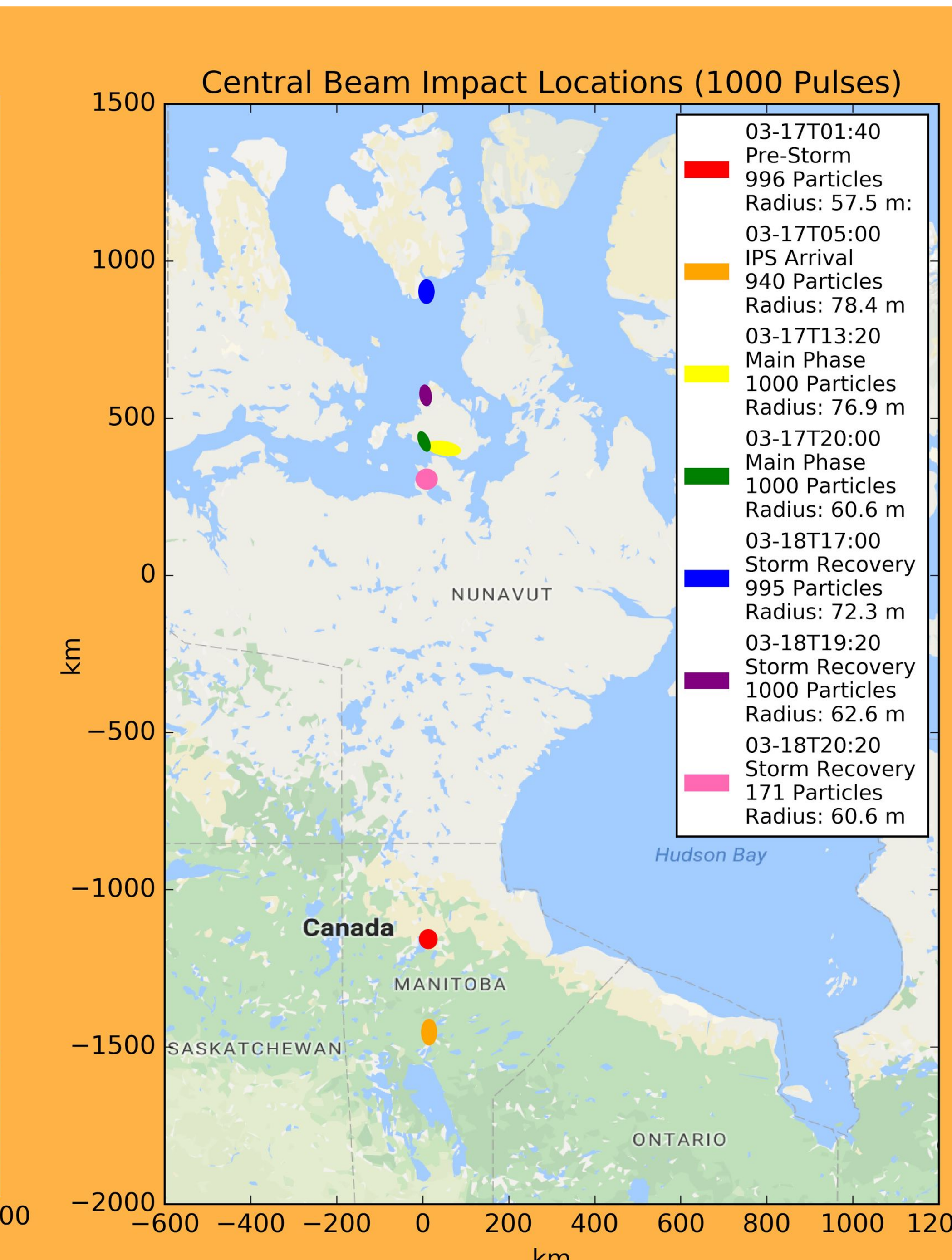


Fig. 6 Final beam spot locations for two pulse simulations with latitude and longitude relative to mean

Fig. 7 Final beam spot locations for 1000 pulse simulations with latitude and longitude relative to mean

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