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Year-end report on FY13 activities for J8A6
Greg Cunningham and Mike Henderson

Purpose of work

During the Summer of 2012, several video-teleconference sessions were held to discuss a collaboration amongst LANL, LLNL and SNL that would combine LLNL's capability to simulate the early-time state of the fission fragment debris from a high-altitude nuclear explosion (HANE) with LANL's Fokker-Planck diffusion code for simulating the long-term evolution of a trapped radiation belt formed from the beta decay of the debris. The purpose of the collaboration would be to demonstrate an 'end-to-end' computational model that would calculate the effect of a trapped radiation belt produced by a HANE on space-based assets. It was thought that demonstrating such a capability to potential sponsors could result in follow-on funding to improve the capability of such a model.

Executive summary

The Russian-3 (R3) HANE, a 60 km high-latitude burst with yield estimated at 300 kt, was chosen for the demonstration. This test was selected because it allowed LLNL to leverage existing funding, which was directed at extending LLNL's capability to simulate HANEs at atmospheric altitudes (<100 km). David Larsen (LLNL) developed a new particle-tracing code that tracks monoenergetic electrons of various energies from a point source as they interact with the atmosphere, losing energy and 'pitch-angle scattering' as they are transported. A relatively large fraction of the initial electrons are able to escape the atmosphere and were handed off to LANL for further processing to calculate the effect on space-based assets. LANL binned the electrons into a phase-space density as a function of energy and equatorial pitch-angle and showed that all of the electrons would travel along field lines to the conjugate point in the Southern hemisphere, where they would likely be absorbed, because their equatorial pitch-angles were too field-aligned to permit them to 'mirror' above the atmosphere and be 'trapped'. Thus, the initial LLNL output did not produce any trapped electrons to input into LANL's diffusion code and so no study of the long-term evolution of the trapped population and its effect on space-based assets could be performed. It was recognized that LLNL's calculation did not properly model the low-probability, large-angle scattering associated with a single Coulomb interaction between a beta-decay electron and the nucleus of the neutral particles in the high atmosphere, which would be the dominant interaction above some altitude (>100 km) and might allow the electrons to be pitch-angle scattered sufficiently to become trapped. A second LLNL calculation that properly included this single-interaction probability was conducted and the output processed by LANL. It was shown that a small fraction of the initial population ($\sim 0.01\%$) would be 'locally trapped'; however, even this small population would likely be absorbed within a few minutes as the electrons drifted around earth and eventually ended up on field lines where they would be absorbed in the atmosphere. The output of the second LLNL calculation was found to produce about 4x fewer backscattered electrons than previous work (Selesnick et al 2012), and so the remainder of the FY13 LANL effort on the project was aimed at trying to resolve this discrepancy. LANL implemented a stochastic differential equation to simulate the backscatter process so that the results could be compared to Larsen and Selesnick. Initial results from this capability have been obtained, but no quantitative comparison to Larsen or Selesnick has been done yet.

Background

In this section of the report, we very briefly review the magnetic mirroring of trapped electrons, the Russian-3 (R3) HANE and observations of a trapped electron population resulting from the blast, and Coulomb interaction of beta decay electrons with neutral particles and ions in (and above) the atmosphere.

Electron motion in earth's magnetic field

In order for beta decay electrons produced in the atmosphere during a HANE to become 'trapped' by the magnetic field surrounding earth, the electrons must first exit the atmosphere and then change their pitch angle (the angle between the velocity vector of the particle and the magnetic field vector) so that they do not enter the atmosphere at the conjugate point in the other hemisphere and become absorbed. A key concept that is applicable here is the conservation of the first adiabatic invariant of motion, $\mu = \frac{p^2 \sin^2(\alpha)}{2mB}$, where p is the electron's total momentum, α is the local pitch angle, m is the mass of the electron, and B is the local magnetic field strength. Because this invariant is conserved along the electron's path (in the absence of scattering), as the electron moves along a field line and the field strength changes, so does the pitch angle, in order to conserve μ . The value of the pitch angle at the equator, typically where the field strength is at a minimum, is called the equatorial pitch angle, α_{eq} . As the particle moves away from the equator, the magnetic field strength increases and so the local pitch angle must also increase, until it hits 90 degrees and there is no parallel momentum. At this point, the particle 'mirrors' and returns back toward the equator. If the mirror point is above the atmosphere in the Northern/Southern hemisphere, then we say that the particle is out of the Northern/Southern bounce loss cone. If the particle is outside both the Northern/Southern bounce loss cones, then it is locally 'trapped' since it will bounce back and forth along the field lines unless it is scattered. Since μ is an invariant and the electron energy is also conserved in a static magnetic field, the magnetic field strength at the mirror point is also an invariant. Furthermore, because the magnetic field has a gradient and the field lines are curved, the particle will experience gradient-curvature drift around earth. The drift period around earth is on the order of 10's of minutes for an MeV electron. Finally, because earth's magnetic field is not a dipole, the location of the mirror point may change quite substantially as a function of longitude, so that the mirror point is outside the atmosphere at some longitudes, and inside the atmosphere at other longitudes.

The Russian-3 high-altitude nuclear explosion (HANE)

The Russian-3 (R3) HANE, the 5th test of the Soviet 'K' project [2], occurred on November 1, 1962, at an altitude of ~60km, with a yield of ~300kt. The location is not precisely known, but the missile was launched from Kapustin Yar toward the ABM test range at Sary Shagan, Kazakhstan, which is located at 46°23'N 72°52'E. The Sary Shagan location produces a McIlwain L of 1.78. Trapped electrons were observed by four satellites, including Explorer 15, centered at a McIlwain L of 1.765 in a narrow range (FWHM~0.037) [3]. The trapping fraction is estimated to be 0.2% [4]. The fact that any trapped electrons at all were observed has not been explained, although there are several possible explanations.

Since the burst was well within the atmosphere, any electrons that were produced in the atmosphere would necessarily have pitch angles that force them to mirror within the atmosphere, unless they are scattered within the first bounce (~1 second). Various mechanisms for pitch-angle scattering electrons during this first bounce have been proposed, including waves generated by the MeV electrons themselves. It is possible that fission fragments made their way out of the atmosphere and while moving to the conjugate point beta decayed and produced electrons with pitch angles that allow them to be trapped. However, the size of the burst cavity is expected to be quite small so that fission fragments have no access to the low-density region outside the atmosphere via the extreme points in the cavity, and the energy loss suffered by the fission fragments as they attempt to exit the atmosphere is thought to be so great that no fragments exit the atmosphere.

Interactions between the beta-decay electrons and atmosphere

As a step toward constructing a code that could be used to predict trapped electrons resulting from a HANE in the atmosphere, David Larson (LLNL) implemented a capability to track monoenergetic electrons in an ambient magnetic field from a point source in the atmosphere, allowing the electrons to scatter and lose energy due to collisions with the atmosphere. The magnetic field model used for the R3 calculation is the International Geomagnetic Reference Field, or IGRF, relevant for the date and location of the R3 event. The model for the mass densities and temperatures of the background neutrals, ions, and electrons up to 500 km altitude is taken from NRL's MSISE-2000, using solar activity relevant to R3. The first instantiation of this code used a Fokker-Planck type equation derived for dense plasmas [1] to compute the mean-squared change in the angle of the velocity vector in response to interactions with ambient ions and electrons, as well as energy loss. The individual scattering angle probability distribution, used to calculate the mean-squared angle, uses a Rutherford type equation where the minimum scatter angle depends on the Debye length, which is relative large for ions and electrons, but is on the order of the atomic electron cloud for neutrals. This model assumes that there are a large number of Coulomb 'collisions' between the electron and the ambient population, which is an accurate assumption up to ~120 km altitude. Above that altitude, the mean-squared change in angle is tiny due to the low probability that an electron will have any Coulomb interactions at all with the atmosphere. Thus, using this model, the electrons are stuck with pitch angles that imply mirror points in the atmosphere, since essentially no scattering takes place once the electrons leave the atmosphere.

Given that the Fokker-Planck type equation used in the first instantiation of LLNL's code assumes a large number of collisions, it is not appropriate for modeling the low-probability large-angle scattering from the tenuous population of neutral particles above 120km. In this case, the probability of a single Coulombic interaction between the electron and a neutral particle must be calculated by integrating the line of sight mass of neutral particles seen by the electron, and the angle of scatter must be sampled from the Rutherford-type distribution. Larson implemented this 'single-scatter' model in his code as an adjunct to his Fokker-Planck type equation and uses it when the number of collisions during a timestep is expected to be very small.

Results

In this section, we report on the results that were obtained during FY13 on the project, including the post-processing of the LLNL outputs, assessment of trapping fractions, and development of a stochastic differential equation code to validate Larson's 'single-scatter' addition to his electron tracking code.

Post-processing of LLNL outputs

The output of Larson's code is a list of electrons that have escaped the atmosphere, with the Lorentz factor, local pitch angle, and geographic location of each electron listed in the file. There is a separate file for each electron energy that is run: 1,2,4,6,8, and 10 MeV. These output files need to be post-processed into a form that is suitable for ingestion into the LANL diffusion code, called DREAM3D. DREAM3D implements a 3D diffusion equation on the phase-space density (PSD) using operator splitting. First, a 1D 'radial diffusion' equation is implemented to model the effects of ULF wave-particle interactions for each pair of 1st and 2nd invariants of motion, μ and K , where μ is the invariant described above associated with the gyro motion of the electron and K is the invariant of motion associated with the bounce motion of the electron. Second, the PSD is resampled as a function of momentum, p , and equatorial pitch-angle, α , and a 2D diffusion equation is implemented to model the effects of VLF wave-particle interactions. In both cases, the PSD specifies the number of electrons per unit 3-dimensional volume per unit 3-dimensional momentum volume, sampled either as a function of μ , K and L , or as a function of p , α , and L . In order to obtain $PSD(p, \alpha_{eq}, L)$ from the LLNL output files, the following steps were taken:

1. For each electron, the geographic location was used with the IGRF field model to
 - a. map the electron to the equator, and conservation of the 1st invariant was used to compute the equatorial pitch angle
 - b. calculate the McIlwain L of the electron
 - c. calculate the momentum from the Lorentz factor
 - d. use the momentum, equatorial pitch angle and McIlwain L , to increment the correct bin in (p, α_{eq}, L) and produce a 'probability distribution' as a function of bin index
2. Divide the number of electrons in each bin of (p, α_{eq}, L) , produced in step 1 by the bin size in coordinate space (basically the volume of the drift shell $[L, L+dL]$) and momentum space (the size of the momentum bin spanned by $[p, p+dp] \times [\alpha_{eq}, \alpha_{eq}+d\alpha_{eq}]$) to calculate the PSD from this energy.
3. Combine all energies by multiplying each individual PSD by the Carter-Reines fission beta spectrum (4.74 betas per fission integrated over energy), the device yield (300 kt), and the number of fissions per kt ($1.37e23$).

The Northern and Southern bounce loss cones were also calculated for each individual electron, and a tally of the number of electrons that were 'outside' each loss cone was computed.

Results from LLNL Fokker-Planck code

The output of LLNL's Fokker-Planck type code for tracking electrons out of the atmosphere was post-processed using the steps outlined above. The output for the 4 MeV electron run is in Figure 1, while the probability distribution for all energies computed as a result of steps 1a-1d is in Figure 2, and the overall PSD produced by step 3 above is plotted in Figure 3.

Figure 1. The raw output from LLNL's Fokker-Planck code for 4 MeV electrons, binned by altitude and local pitch-angle.

Figure 2. The log of the probability distributions for 1 MeV (top), 2 MeV, 4 MeV, 6 MeV, and 8 MeV (bottom) vs momentum on the horizontal axis (0-10.5 MeV/c) and equatorial pitch angle on the vertical axis (0-20 degrees).

Figure 3. The log PSD(p, α_{eq}) obtained by combining the weighted probability distributions of Figure 2.

The results of this initial run show that the maximum equatorial pitch angle is ~ 17 degrees, the Northern bounce loss cone angle, which is well within the Southern bounce loss cone angle of ~ 21.5 degrees. This means that all of these particles will want to mirror deep within the atmosphere at the Southern conjugate point, and there is no trapped population to run through DREAM3D to calculate the evolution of the trapped population and impact on space-based assets, as hoped.

Results with LLNL single-scatter code modification

The population of electrons that was computed above was adiabatically transported down the field lines to an altitude of 200km above the Southern conjugate point, and the LLNL code with the modification to include low-probability single-scatter events was used to see whether ‘backscatter’ off the atmosphere at the Southern conjugate point could produce a trapped population. The log PSD from this run is compared to the previous run in Figure 4, and the results indicate that a significant fraction ($\sim 2\%$) of the low-energy population does, indeed, backscatter. This population will head back toward the Northern conjugate, and on its way create a ‘two-stream instability’ with the electrons that are still moving toward the Southern conjugate point. Such an instability might create waves that can pitch-angle scatter the electrons out of the loss cone and into the trapping region. A very small fraction of the original population (0.01%) possesses equatorial pitch angles after backscattering that are already larger than both the Northern and Southern bounce loss cone angles. These particles will be trapped for a few minutes until the electrons drift around earth and eventually enter a region where their mirror points enter the atmosphere, at which point the vast majority of them will be absorbed, and a few percent will be backscattered, a negligible fraction of the original population.

Figure 4. The log $\text{PSD}(p, \alpha_{\text{eq}})$ after running the electrons into the atmosphere at the Southern conjugate point using the low-probability single-scatter event model (left) compared to the log PSD at 200 km above the Southern conjugate point (right) as a function of momentum along the horizontal axis [0,10.5] MeV/c, and equatorial pitch angle along the vertical axis [0,22] degrees.

Stochastic differential equation code

The single-scatter event modifications that Larson made to the LLNL electron transport code produces a smaller backscatter fraction than is published by Selesnick [5]. Larson is attempting to resolve the source of this discrepancy. In the meantime, LANL is developing its own stochastic differential equation (SDE) code to contribute to the resolution.

Conclusion

In summary, the single-particle tracking code that LLNL began the collaboration with assumed a very large number of individual scatter events and used the mean-squared angle of scatter to compute the pitch-angle scatter of HANE electrons caused by the atmosphere. LANL took the output of the LLNL code and found that no electrons were scattered into pitch angles that would cause the electrons to be permanently trapped; thus, this model does not predict the observed trapping of electrons during the Russian-2 HANE. The initial LLNL model is appropriate for relatively low altitudes (<100 km), but LANL pointed out that it is inappropriate for modeling the more tenuous atmosphere above 100 km, where low-probability, high-angle, Rutherford-type scattering of electrons off of neutral atoms likely dominates. LLNL modified their code in order to account for these ‘single-scatter’ interactions at higher altitudes. The new capability shows that a few percent of the electrons can backscatter off the atmosphere at the southern conjugate, but will not remain trapped for very long without additional scattering. Furthermore, the LLNL code underpredicts the backscatter fraction as compared to other recently published work, and so LANL is building its own single-event scatter code to compare with the LLNL code and the published literature. We expect to use the new LANL code during FY14 to study whether low-probability, high-angle scattering can cause any electrons to become ‘permanently’ trapped for the Russian-2 HANE.

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