DREAM:
An integrated space radiation nowcast system for natural and nuclear radiation belts

Geoffrey D. Reeves
Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, NM

ABSTRACT

The natural space environment continues to surprise us. We recently witnessed the quietest solar minimum in the past 100 years, casting huge uncertainties on our expectations for approach to Solar Maximum. The overall space environment is made up of many related but independent parts. The Dynamic Radiation Environment Assimilation Model (DREAM) focuses on the spacecraft charging environment. DREAM-RB (Radiation Belt) covers the internal charging (penetrating radiation) environment and DREAM-RC (Ring Current) covers the external, surface charging environment. A third component of DREAM is an electron source model (ESM) that calculates the trapped electron environment produced by high altitude nuclear explosions (HANE). All three major components of DREAM have undergone accelerated development over the past 18 months and now comprise an integrated code system for real-time “nowcasting”, for retrospective analysis of events, and for assessing threats from nuclear scenarios. DREAM-ESM has many similarities to the legacy SNRTACS code system but was developed to give us a modern code architecture with well-understood physics that could be integrated into the full DREAM system. The core of that system is the radiation belt model that uses data assimilation from geosynchronous, GPS, and other radiation measuring platforms to provide a highly accurate nowcast of the penetrating electron environment. DREAM includes codes that implement spacecraft tracking using the space catalog to calculate the specific internal charging and dose rate conditions at a specific satellite of interest. Targeted applications include alerts/warnings, anomaly resolution for more reliable operations, and attack/anomaly assessment for space situational awareness. The DREAM system is written to be fully compliant with Service Oriented Architecture standards and even has an iDREAM Space Weather app for the publicly-available space weather services.

1. INTRODUCTION

The Dynamic Radiation Environment Assimilation Model (DREAM) was developed at Los Alamos National Laboratory to understand and to predict hazards from the natural space environment and artificial radiation belts produced by high altitude nuclear explosions (HANE) such as Starfish. DREAM was initially developed as a basic research activity to understand and predict the dynamics of the Earth’s radiation belts. It uses Kalman filter techniques to assimilate data from space environment instruments with a physics-based model of the radiation belts. DREAM can assimilate data from a variety of types of instruments and data with various levels of resolution and fidelity by assigning appropriate uncertainties to the observations. Data from any spacecraft orbit can be assimilated but DREAM was originally designed to work with input from the LANL space environment instruments on Geosynchronous and GPS platforms. With those inputs, DREAM can be used to specify the energetic electron environment at any satellite in the outer electron belt whether space environment data are available in those orbits or not. Even with very limited data input and relatively simple physics models, DREAM specifies the space environment in the radiation belts to a high level of accuracy.

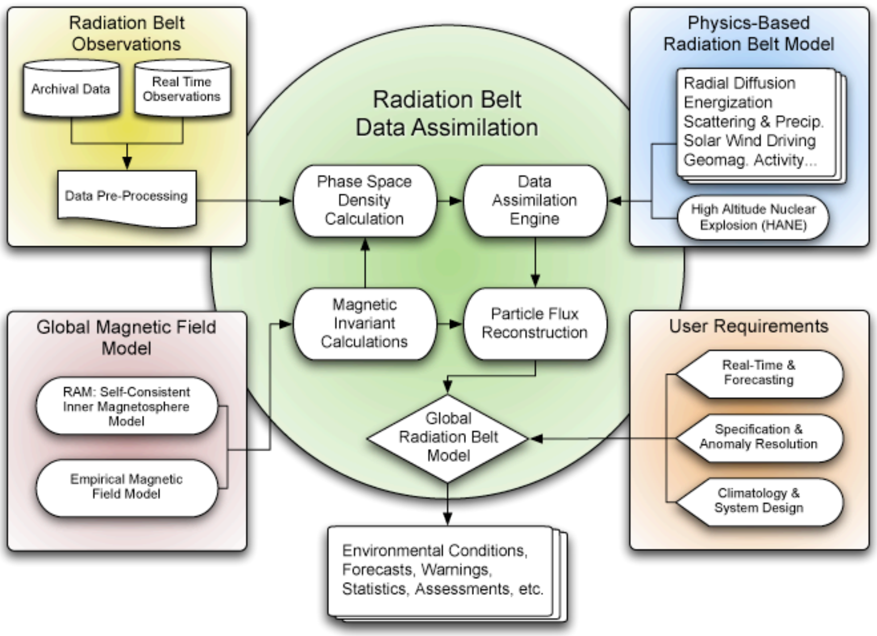

Figure 1: The organizational structure of DREAM is based around a central data assimilation engine using Kalman Filter techniques. Archival or real-time data are preprocessed and transformed into phase space density using magnetic invariants calculated from a global magnetic field module. The Kalman Filter combines observations and physics-based models into an optimized global specification of the radiation belts. In order to efficiently utilize the large, multi-dimensional data volume customized post-processing and user interfaces are used.

The numerical framework for the Dynamic Radiation Environment Assimilation Model is modular and flexible in order to accommodate a variety of physical scenarios and modeling configurations [*Reeves*, 2010; 2011]. DREAM does not consist of a single code or even a single language. Although it is a heterogeneous system, it is fully functional and has been run for a variety of intervals of scientific interest as well as for routine production of model outputs spanning several years of radiation belt dynamics. DREAM currently includes two implementations. The 'full-service' implementation includes all of the components that are available at any given time. It allows both routine analysis using components that have been tested and validated or, separately, the development and debugging of modules with new or advanced capability. The second implementation is designed to run on workstation-level platforms using real-time space weather observations and an interactive user interface. It uses the same modules as the full-service implementation but integrates them into a stand-alone, platform-independent code. The real-time implementation uses a more limited subset of code modules. It is also used to provide web services through standardized Service Oriented Architectures.

The objectives of the DREAM model are to provide quantitative analysis of the risks to satellites from radiation belt electrons. Radiation belt electrons are sometimes referred to as "relativistic electrons" because the electrons have energies of millions of electron volts (MeV), much larger than the rest mass energy. At these energies the electrons travel nearly the speed of light and can penetrate typical shielding used by satellites and space instruments. When the electrons penetrate the interior of the satellite they deposit their charge in materials causing a variety of damaging effects including radiation damage and, when materials cannot dissipate the charge, destructive electrical discharges.

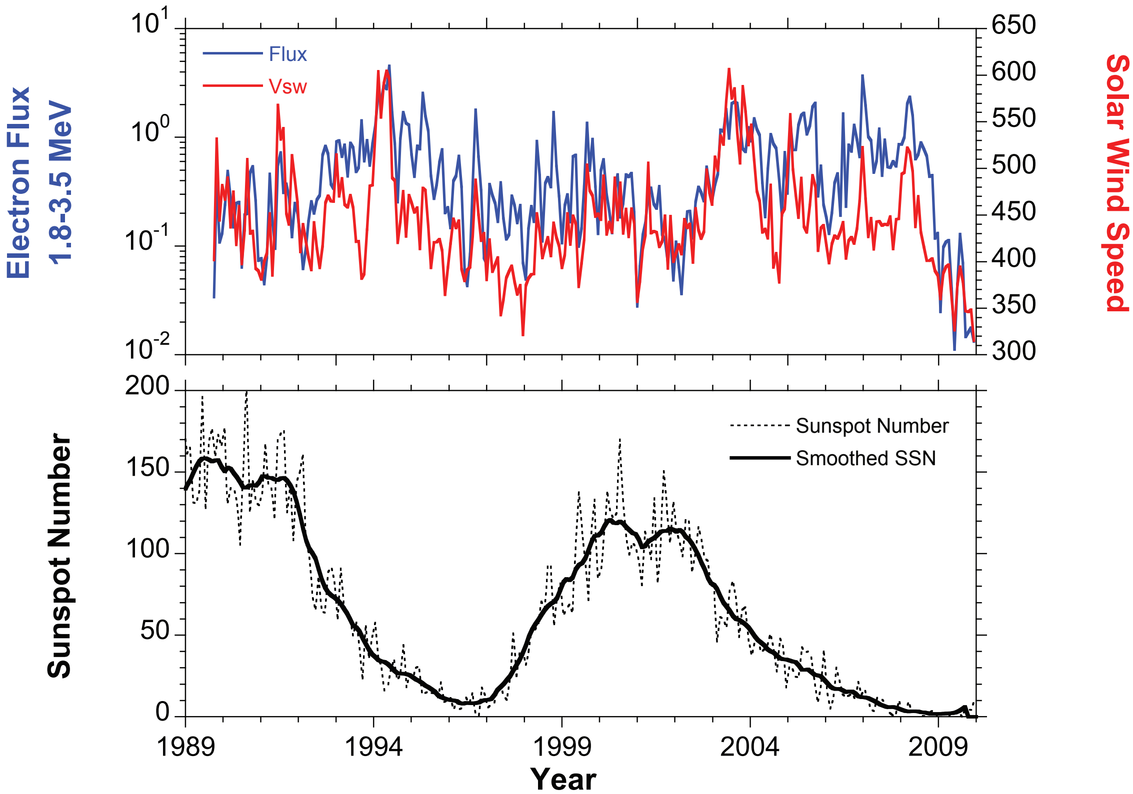

Figure 2: The top panel shows the long-term variation of geosynchronous radiation belt electrons (blue) and velocity of the solar wind (red) which is, in part, responsible for radiation belt variations. Both quantities are 27-day averages (the rotation period of the sun as seen from the Earth) in order to smooth short-term solar activity. The bottom panel shows the sunspot number and smoothed sunspot number from 1989-2010. Solar activity and radiation belt dynamics are complex and often surprising. The solar minimum of 2010 was the lowest observed for over 100 years. (From Reeves et al., [2011])

The intensity of radiation belt electrons changes by many orders of magnitude and changes occur as fast as hours. These fast changes are superposed on longer-term changes that are caused by the solar activity cycle (sunspot cycle) and by geomagnetic storms. Figure 2 shows some of interesting variations of solar activity and radiation belt dynamics seen over the last 20 years. Starting in 1989 LANL has flown the SOPA and ESP instruments at geosynchronous orbit to observe changes in the radiation belts and effects on satellites. This forms one of the largest and most complete set of Space Weather observations in existence and, along with GPS observations, is the fundamental data set used by DREAM. (Other LANL measurements can extend the record back to 1979.) Figure 2 shows most of solar cycle 22, all of solar cycle 23, and the beginning of the new solar cycle, 24 [*Reeves et al.*, 2011]. Solar activity and radiation belt dynamics are complex and often surprising. The solar minimum of 2010 was the lowest observed for over 100 years. At the same time the solar wind speed and the intensity of the Earth's radiation belts dropped to the lowest levels ever observed. The remarkable conditions observed in the recent solar minimum led many researchers to question our basic assumptions about solar activity: in particular the assumption that past solar conditions are a good predictor of future activity.

The changes in the Earth's space environment and their adverse effects on technological systems are referred to as Space Weather (or SWx). As with "normal", i.e. tropospheric weather, space weather has a variety of different facets that can adversely affect space and ground-based systems. In the case of tropospheric weather we know that different systems can be affected by different aspects of the weather: wind, rain, heat, cloud cover, etc. Similarly different systems can be affected by different aspects of space weather. Solar activity can produce x-ray emissions and solar energetic particles (also called solar cosmic rays) which can produce direct effects on space systems. Solar activity also drives activity in the Earth's magnetosphere and ionosphere. Ionospheric space weather effects include communications interference and degradation of GPS navigation signals among others. Magnetospheric space weather effects include surface charging, internal charging, and total dose effects and it is the quantitative prediction of those effects that is the objective of DREAM.

The severity of space weather is also a function of the solar cycle but not all space weather effects are most severe at solar maximum. Solar energetic particle events and coronal mass ejections (CMEs) are most common near solar maximum but, as figure 2 shows, the intensity of the radiation belts actually peaks somewhere between solar maximum and solar minimum (in the so-called declining phase). Therefore standard measures of solar activity, such as sunspot number or flares, are poor predictors of radiation belt intensity. Even geomagnetic storm activity is an unreliable indicator. The intensity of a storm and the intensity of the radiation belts are not correlated and, in fact, only about half of all storms actually increase the intensity of the radiation belts [*Reeves*, 1998; *Reeves et al.*, 2003].

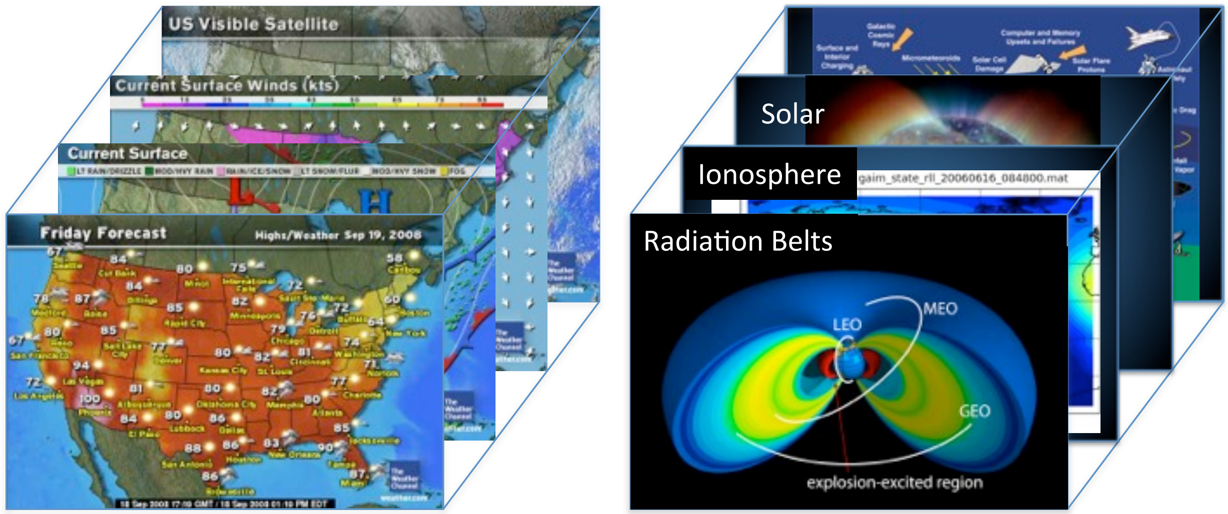

Figure 3: As with weather on the Earth's surface, space weather has many different aspects that can pose risks to different systems. DREAM is designed to calculate the risks posed by penetrating electrons in the Earth's radiation belts.

2. STRUCTURE OF THE DREAM MODEL

Figure 1 illustrates the basic organizational structure of the DREAM model. There are 5 basic components, or modules, that make up the overall DREAM model. Those are observations and pre-processing or radiation belt observations, modeling the global geomagnetic field, a physical model of the radiation belts, a data assimilation engine that combines the physical model, magnetic model, and observations, and finally a post-processing module that extracts the specific information needed based on use requirements.

2.1 Observations and Pre-Processing

Both real-time and archival data sources require some amount of pre-processing as illustrated by the yellow module in figure 1. Pre-processing of radiation belt data can include a variety of steps and can produce results with high confidence levels but can often produce results with large uncertainties. The precision and accuracy of the original measurements are typically known (to some degree) prior to launch. However, detailed on-orbit cross-calibration and modeling of instrument response can refine and improve the observations. Often, assumptions about the shape of the energy spectrum or pitch angle distribution must be applied. Typically, ancillary data and/or models also need to be applied – for example background subtraction, etc. Ideally, some independent measure of the total uncertainty from all sources should be applied. We also note that equal care must be applied to data sets that are not assimilated, but rather are used to validate the results. This too is included in the radiation belt observations module in figure 1.

2.2 Global magnetic fields

The motion of charged particles in the magnetosphere is organized, to first order, by the large-scale electric and magnetic fields. For particles with energies greater than tens of keV, the ExB drift motion can be neglected and magnetic drift dominates. Magnetic drift can be organized around three periodic motions each with an associated adiabatic or 'magnetic' invariant: gyration around the magnetic field, bounce along the field between magnetic mirror points, and longitudinal drift around the Earth along a drift shell (or L-shell). While local magnetic field measurements are available from a number of satellites, there is no way to directly observe the entire, global magnetic field. Therefore, radiation belt modeling also requires a model of the global geomagnetic field which is represented by the red module in figure 1.

The simplest assumption of a tilted dipole field is grossly inadequate to describe the distorted, dynamic geomagnetic field. Stretching and compression of the field changes the both the local field vector and the pitch angle distribution of particles on the field line. The storm-time ring current diamagnetically 'inflates' the field and adiabatically distorts particle drift orbits while simultaneously changing their energy and pitch angles. These are not small effects and radiation belt models for space weather applications must include them to achieve even minimal accuracy. DREAM can, in principle, use any representation of the geomagnetic field ranging from static models like [*Olson and Pfitzer*, 1977] to global MHD models. We believe the best results can be obtained with a kinetic model of the ring current with self-consistent magnetic fields. The event-specific Ring Current and Atmosphere Model with Self-Consistent B fields (RAM-SCB) model was specifically developed for DREAM. It is a comprehensive model of the inner magnetosphere that self-consistently describes particle dynamics in pressure balance with the geomagnetic field and driven by observational inputs of particle fluxes at geosynchronous orbit.

2.3 Physics models

Physics-based models of the radiation belts can come in a variety of forms. Diffusion models are the most common. Radiation belt diffusion equations use phase space density (psd) as the free variable. Phase space density is defined as the flux over the square of the particle momentum ($f=j/p^2$) which is conserved a conserved quantity whereas flux or energy spectrum are not. Space instruments do not directly measure phase space density. Rather, they measure particle flux as a function of energy and the viewing direction of the detector. Some satellites include comprehensive observations that provide differential flux over a broad range of energies and include magnetic field measurements that can be used to convert angular-resolved measurements into pitch angle distributions. Other satellites include only targeted observations from instruments that may provide limited angular resolution, omin-directional or hemispherical measurements, and/or lack a magnetometer to convert inertial coordinates to pitch angles. They may also have limited energy coverage and/or limited energy resolution up to and including dosimeters that measure all particles with sufficient energy to penetrate a given thickness of shielding. (e.g. [*O'Brien et al.*, 2008])

Using the global geomagnetic field model, we can calculate the magnetic invariants that correspond to a given electron energy and pitch angle at a given time and spatial location. This, then allows us to calculate phase space density as a function of those magnetic invariants as required by the physics models. The physics-based radiation belt models (represented by the blue box in Figure 1) can include a variety of processes including radial diffusion, particle energization, pitch angle scattering, precipitation into the atmosphere, detrapping and magnetopause loss, etc. Each process may be parameterized in terms of geomagnetic activity indices (such as Kp or Dst) or they may be directly calculated from measured quantities (such as wave spectra). Some processes may be parameterized by characteristics of the solar wind and interplanetary magnetic field (IMF). In some cases, the physical relationship between input parameters and a given process can be directly modeled. In other cases parameters may be known statistically but not known for a particular time, place or event. In those cases the data assimilation can be used to optimize free parameters as it assimilated observations into the physics models.

2.4 Artificial radiation belts

For national security applications, DREAM can also include a module that calculates the injection, trapping and dynamics of artificial radiation belts from high altitude nuclear explosions (HANE) [*Tokar*, 2007; *Winske et al.*, 2009]. The most well-known and well-documented HANE belt was produced by the Starfish high altitude nuclear test known as Starfish. HANE electrons are produced by the beta decay of radioactive debris from the nuclear explosion. The trapped HANE electrons form a new, artificial radiation belt. We have developed a new electron source model (DREAM-ESM) that allows us to simulate HANE belts under a variety of initial assumptions. Fortunately for modeling purposes, electrons are electrons regardless of their source and the intermediate and long-term evolution of the HANE electrons are subject to the same physical processes of transport, scattering, loss, or acceleration that “natural” radiation belt electrons are. DREAM allows a HANE source to be incorporated along with the assimilated observations and physics model to quantitatively model a wide variety of hypothetical scenarios and the “space weather” risks associated with each.

2.5 Data assimilation

The data assimilation engine combines the observations (phase space density as a function of magnetic invariants) with the physics model. It represents the physical system at any point in time using a state vector. In the simplest form, our state vector is the phase space density as a function of drift shell (parameterized by ‘L’) which is binned into an array of 100 elements of 0.1 R_E. At each time step the state vector is compared against available observations for those elements of the array that have new observations. The state vector is “adjusted” according to the observations and the errors that have been assigned to the model state an to the observations. Then, the new state is projected ahead in time by the physics model and the process is repeated. DREAM typically uses one of two variations on the standard Kalman Filter. An extended Kalman Filter refers to a technique that includes additional parameters as part of the state vector. One example is to use phase space density at the boundary of the model as a free parameter. An ensemble Kalman Filter advances the state vector for a single time step using random statistical variation in the starting state vector or in the model.

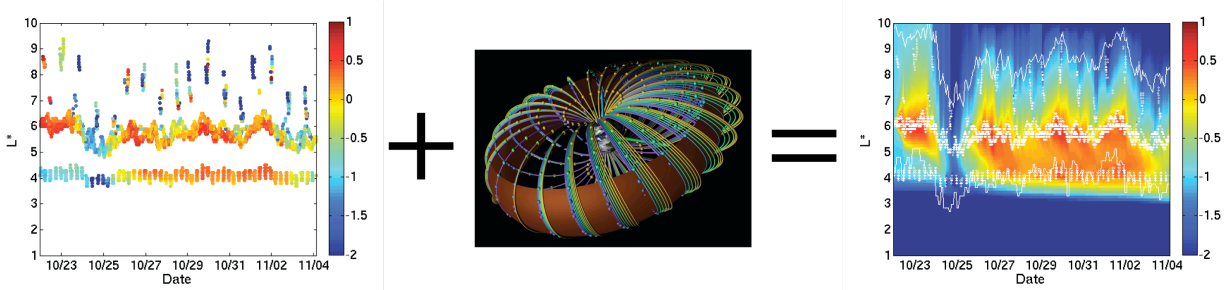

Figure 4: An illustration of the data assimilation technique. The data to be assimilated are shown in the left hand panel with equatorial phase space density color coded and plotted as a function of L-shell (altitude in R_E) and time. The middle panels represents the DREAM physics model and the right hand panels shows the results of the assimilation which fills in the global (spatial and temporal) space required for useful operations.

2.6 User requirements

When the assimilation step is complete the result is a global representation of the radiation belts. At this stage though, the representation is still given by phase space density as a function of magnetic invariants. For validation or for applications, the first step in the process must be reversed and phase space density transformed back into particle flux as a function of energy, pitch angle, time, and spatial location. The transformation can either be done for a specific satellite trajectory or calculated for every point in the inner magnetosphere. The resulting global model is five-dimensional (three spatial dimensions, energy, and time) and therefore contains much more information than can be intuitively understood. At this stage it is essential to incorporate user requirements (orange box) to produce specific information tailored to specific users and applications. Synoptic views provide a global picture with reduced dimensionality. A common format shows flux at fixed energy as a function of L-shell and time. More satellite-specific applications might require dose as a function of time along a specific satellite trajectory. An even more useful application would compare current conditions against the historical probability distributions derived from long-term reanalysis products (e.g. radiation belt climatology).

One important feature of DREAM is that it has been designed with flexibility in mind. It can produce a variety of space weather products to meet a variety of user needs without changes to other parts of the code. Likewise, it is not designed to use any specific set of satellite observations. The same codes will run in the same way whether there are data from ten satellites in ten different orbits or just one. It is robust to heterogeneous data from different satellites providing data over different time spans and robustly accommodates data gaps with no observations. Different geomagnetic field models and different physics-based radiation belt models can be configured together or independently. Because the components work together in the same way regardless of configuration the results from different configurations can be compared quantitatively against one another as the model is developed, tested, and refined.

3. WEB SERVICES

The real-time version of DREAM has been designed to run continuously in real time on modest desktop class computers. It can run under Linux, Windows, and Mac OS to provide information on the current radiation belt environment conditions. It also includes tools for environment and satellite orbit visualization. This version is also the version that provides web services that provide digital data and interactive plots of the environment. The web services are in beta version at http://dream.lanl.gov/. The beta web service allows us to test the software and displays in a quasi-operational setting but we have implemented it early in the development cycle while there are still known artifacts and limitations that are described in our previous paper [*Reeves*, 2010].

Web services (or Service Oriented Architectures - SOA) are rightly viewed as the wave of the future for space situational awareness. SSA requires that we extract actionable understanding out of the vast amount of information that is collected. It is not possible to write a single computer code for each problem of interest. The system has to be distributed, modular, and flexible to meet a variety of needs - both needs that are known now and others that we cannot anticipate. Fortunately web services have become the standard in commercial information-based businesses. An example that is illustrative is Facebook. Say you are reading an article from the on-line version of the New York Times. There's likely to be a button to recommend it on Facebook. Clicking the button produces a URL that contains information such as the title of the article, pointers to a picture, the origin of the request, any comments you decide to add etc. That gets sent to Facebook in a format that Facebook understands and automatically adds to your pages there with links back to the original article.

The critical thing in designing web services is to construct software in ways that anticipate the types of requests that could be made and creates appropriate hooks in the code in order to return desired results. DREAM has been written with those services in mind. Figure 5 illustrates the flow of data within the DREAM framework and the types of services that are being designed for visual displays. One of the first steps is to collect input data. In addition to satellite observations, inputs may include geophysical parameters that characterize general space conditions. Some users may not want the full output from the DREAM model. They may only want to look at the data that go into the model. By making the appropriate service request (through a passed URL) DREAM will return a plot of the input data without running the rest of the code. When DREAM is called by another service a plot may not be the appropriate output. DREAM can also return digital data that can be used directly in some other calculation by some other service.

In it's current state of development, DREAM does not yet provide all the services illustrated in figure 5. It does, however, provide services (using JMS-compliant standards) that can provide direct digital outputs as well as graphical displays for human interpretation. Equally important, DREAM has been designed with the appropriate modularity and the appropriate "hooks" into the code that each component and each calculation can be configured to provide services independently from the other parts of the code.

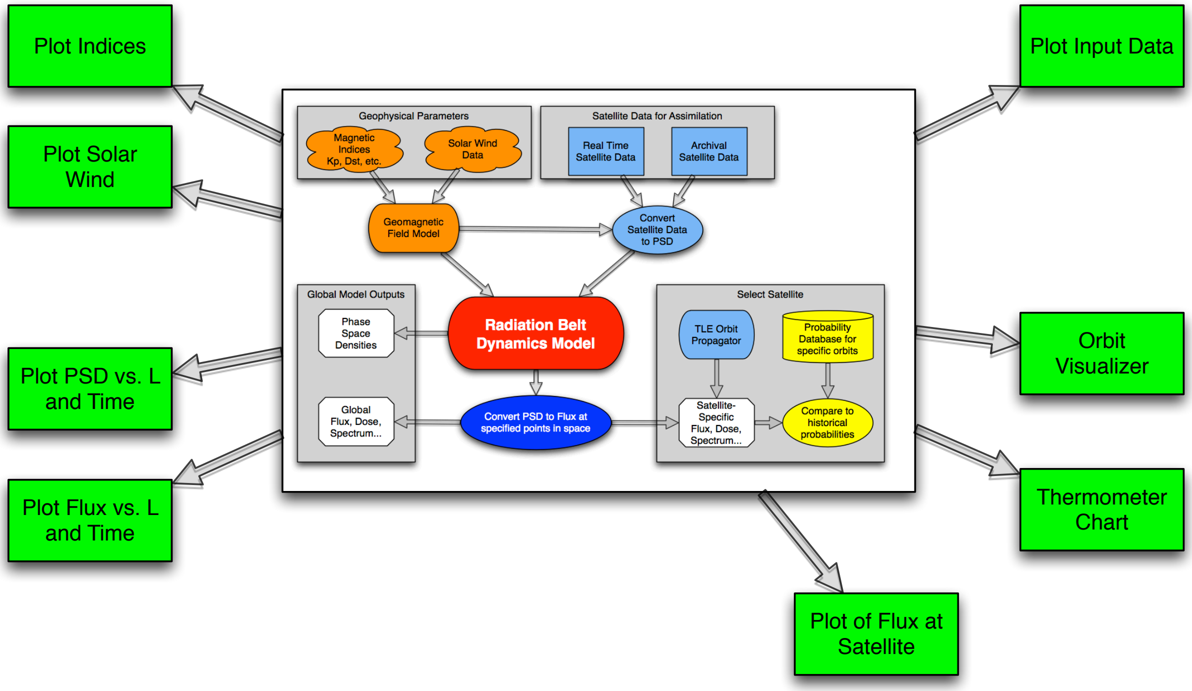

Figure 5: The data flow within DREAM and the various web services that can be provided by different parts of the code.

4. NUCLEAR RADIATION ENVIRONMENTS

As discussed in Section 2, one important part of DREAM is the ability to calculate the electron radiation environment produced by a high altitude nuclear explosion (HANE also known as HAND for "detonation"). Nuclear explosions produce a variety of prompt radiation including x-rays, gamma rays, and neutrons that propagate directly from the site of the explosion and diminish in intensity with the square of the distance from the blast. The same explosion also produces radioactive debris in the form of ions that then decay to produce energetic electrons. Both the ions and electrons have electrical charge so they cannot propagate freely but, rather are trapped in the Earth's magnetic field. Once trapped, the electrons circle the Earth to produce a band (or shell) of radiation that persists for months or years.

The location of the nuclear radiation belt in space depends on the location of the initial explosion and the configuration of the Earth's magnetic field. Explosions at high latitudes extend far into space along the magnetic field lines. An explosion over Alaska or Norway would intersect geosynchronous orbit at an altitude of 36,600 km. An explosion, like Starfish, at very low latitudes also extends out into space but those magnetic field lines only reached an altitude of a few hundred km.

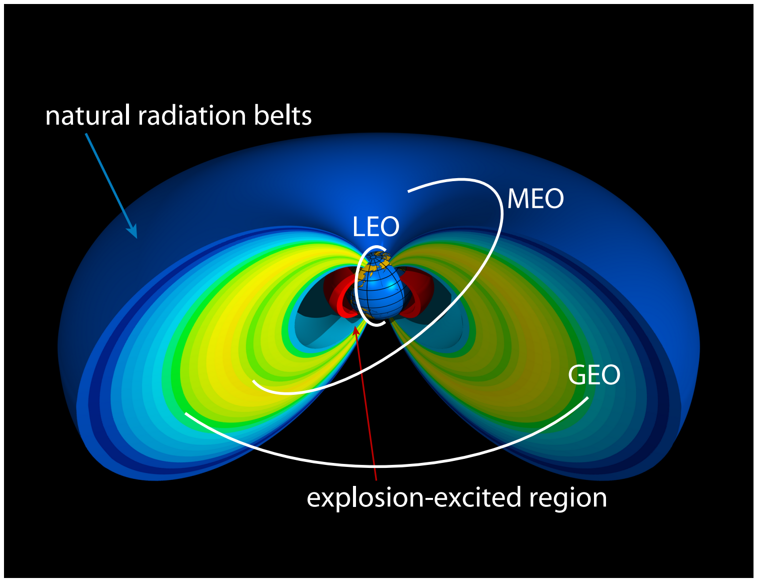

Figure 6: A cut-away view of the radiation belts. The natural radiation belts fill the space around the Earth while a nuclear event forms a band (or shell) around the Earth. The location of the nuclear radiation belt in space depends on the location of the initial explosion and the configuration of the Earth's magnetic field.

Most of the more populated regions of Earth lie at intermediate latitudes where the magnetic field lines extend into space reaching altitudes inside the orbit of the GPS satellites. For that reason satellites in high-altitude orbits are not considered to be at high risk for HANE. Low Earth Orbit (LEO) is a different story. Since the nuclear radiation belt extends from the top of the atmosphere and completely encircles the Earth a HANE radiation belt would affect nearly every satellite in LEO. The magnitude of the effects depends on a number of factors that are calculated in the DREAM model. The location and yield of the burst determines the initial radiation environment. Subsequent evolution over days to years is determined by the same space weather activity that affects the natural belts. Equally important, the orbital parameters of the LEO satellite determines how much time the satellite spends in the nuclear belt and therefore the dose and probability of failure. The "user requirements" module in DREAM includes the capability to select a particular satellite and fly it through the nuclear radiation environment to calculate the specific nuclear radiation environment for that satellite.

5. CONCLUSIONS

The Dynamic Radiation Environment Assimilation Model, DREAM, has been designed to calculate the probability that a satellite will be adversely affected by electrons in the Earth's radiation belts or from high altitude nuclear explosions. The model uses data assimilation which is a powerful technique for combining observations and physical models to obtain more accurate situational awareness. DREAM has been designed with a modular architecture that is well-suited to providing web-based services. DREAM has been tested and validated at Los Alamos National

Laboratory and is currently undergoing further independent testing at the Air Force Research Laboratory. Initial capabilities are already of practical importance for addressing satellite anomalies and resolving whether they are due to natural effects or hostile actions. DREAM is also capable of assessing satellite vulnerability to long-lived radiation belts in specified nuclear explosion scenarios.

Acknowledgements: This research was conducted as part of the Dynamic Radiation Environment Assimilation Model (DREAM) project at Los Alamos National Laboratory. We are grateful to the sponsors of DREAM for financial and technical support.

6. REFERENCES

O'Brien, T. P., et al. (2008), On-Board Space Environement Sensors: Explanation and Recommendations, Aerospace Technical Report, ATR-2008(8073)-4, , The Aerospace Corporation.

Olson, W. P., and K. Pfitzer (1977), Magnetospheric magnetic field modeling,, technical report, McDonnell Douglas Astronaut. Co., Huntington Beach, Calif.

Reeves, G. D. (1998), Relativistic electrons and magnetic storms: 1992-1995, *Geophys. Res. Lett.*, *25*, 11, doi:10.1029/98GL01398.

Reeves, G. D., et al. (2003), Acceleration and loss of relativistic electrons during geomagnetic storms, *Geophys. Res. Lett.*, *30 (10), 1529 , doi: 10.1029/2002GL016513*.

Reeves, G. D. (2010), Integration Of Space Weather Into Space Situational Awareness, proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), Maui, HI, September 13-17.

Reeves, G. D. (2011), The Dynamic Radiation Environment Assimilation Model: DREAM-2011, *Space Weather*, *submitted*.

Reeves, G. D., et al. (2011), On the relationship between relativistic electron flux and solar wind velocity: Paulikas and Blake Revisited, *Journal of Geophysical Research*, *116*, A02213, doi:10.1029/2010JA015735.

Tokar, R. L. (2007), Radial diffusion model for artificial electron injections, Los Alamos National Laboratory Technical Report, LA-UR-07-1472.

Winske, D., et al. (2009), New Model for HANE Energetic Electron Generation and Trapping, Los Alamos Technical Report (OUO).