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Title: The Dynamic Radiation Environment Assimilation Model (DREAM)

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THE DYNAMIC RADIATION ENVIRONMENT ASSIMILATION MODEL (DREAM)

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The Dynamic Radiation Environment Assimilation Model (DREAM) is a 3-year effort sponsored by the US Department of Energy to provide global, retrospective, or real-time specification of the natural and potential nuclear radiation environments. The DREAM model uses Kalman filtering techniques that combine the strengths of new physical models of the radiation belts with electron observations from long-term satellite systems such as GPS and geosynchronous systems. DREAM includes a physics model for the production and long-term evolution of artificial radiation belts from high altitude nuclear explosions. DREAM has been validated against satellites in arbitrary orbits and consistently produces more accurate results than existing models. Tools for user-specific applications and graphical displays are in beta testing and a real-time version of DREAM has been in continuous operation since November 2009.

1. INTRODUCTION to DREAM

The Dynamic Radiation Environment Assimilation Model (DREAM) uses operationally-available observations and data assimilation techniques to specify the space environment globally. The goal is to quantify the hazards to space systems from the space environment in any orbit at any time. DREAM uses techniques and has applications that are, in many ways, similar to those in the more well-known Global Ionospheric Assimilation Models (GAIM). Data assimilation combines limited observations with physical models using techniques, such as Kalman filtering, that optimize the accuracy of the model output. The DREAM model is currently focused on prediction of the electron radiation belts but provides a framework for more generalized space environment forecasting.

DREAM is not a single monolithic code but, rather, a system of coupled codes which may serve specific individual functions but many of which are used in a variety of steps in the processing. The general structure of DREAM is illustrated schematically in Figure 1. The core of the model is a data assimilation cycle that incorporates spacecraft observations, physics-based models, and configurable options in a flexible and expandable architecture. Radiation belt observations can come from a variety of heterogeneous sources and are not limited to specific inputs. At the same time no specific inputs are required either. While we typically run using Los Alamos space environment instruments from GPS and geosynchronous platforms we have also run DREAM using data from GOES, CRRES, POLAR, THEMIS, HEO, and others. DREAM can be run using only a single data source or can assimilate data from many satellites with different orbits, energy channels, temporal resolutions etc.

Likewise DREAM can use a variety of physics-based models of the radiation belts. Our standard runs use a simple Fokker-Planck, 1-dimensional radial diffusion model with source and loss terms added as proxies for energy diffusion (i.e. heating) and pitch angle scattering [*Koller et al.*, 2007]. Observations of the radiation belts are typically in the form of flux as a function of energy and, possibly, pitch angle. The equations of motion for radiation belt dynamics require that flux be converted to phase space density (PSD) as a function of the magnetic invariants related to gyromotion (μ), bounce between mirror points (J, or K), and drift around the Earth (Φ, or L*). In order to calculate these magnetic invariants and convert flux to PSD we require as accurate a model as possible of the dynamic geomagnetic field. DREAM can use any field model ranging from a simple dipole field to empirical statistical models (e.g. *Tsyganenko*, [1989] or, for more complex runs, our kinetic inner magnetosphere model, RAM-SCB, that includes self-consistent calculation of the ring current and geomagnetic field [*Zaharia et al.*, 2006]).

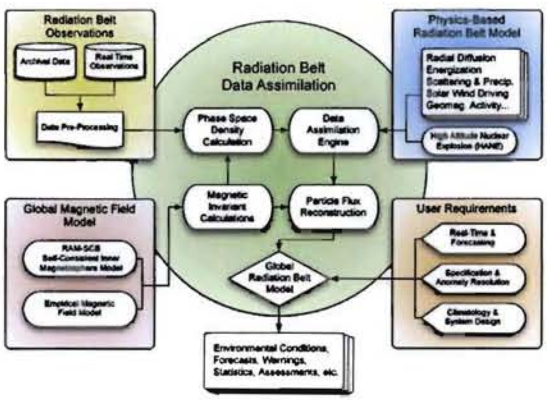

Fig 1. A schematic of the structure of DREAM. The model consists of five basic functional areas with a Kalman filter data assimilation cycle at the heart of the model.

The data assimilation engine is also configurable. To date we have used Kalman filters, Ensemble Kalman filters, and Extended Kalman filters. Other methods are also possible.

In order to provide information that can be used for practical applications we must again use magnetic field models to convert back from phase space density, PSD, to particle flux, fluence, and/or dose. The resulting output is a large, multi-dimensional data volume which, by itself, is much more rich and complete but also much more complex to interpret than the simple line plots that are commonly used for space weather forecasting (e.g. GOES >2 MeV electron fluxes). Therefore DREAM also includes components that allow for customized data products for generalized forecasting or for specific user-defined applications as will be discussed below.

2. HANE-PRODUCED RADIATION BELTS

The DREAM model also includes components that can model the production, trapping, and evolution of HANE-produced electrons [*Winske et al.*, 2009]. Our HANE electron model incorporates two important characteristics. Firstly, we take considerable care to model the motion of radioactive debris ions in the geomagnetic field and consider ions confined in the burst cavity, those precipitating into the atmosphere, and the full motion of trapped ions in the geomagnetic field. The resulting distribution of trapped electrons will have characteristics that depend on where along the field the ions produce beta-decay electrons.

The second important feature of DREAM is its ability to calculate the long-term (days to years) evolution of the HANE belt under realistic magnetospheric conditions. Once they are trapped in the geomagnetic field, HANE electrons are subject to all the same processes as the natural electron population including transport, acceleration, and decay. DREAM uses measurements of the natural environment to determine which processes are operating at a given time and spatial location and then applies those processes to the evolution of HANE electrons. When ambient electrons are accelerated so are HANE electrons. Likewise the time-dependent decay of ambient electrons quantifies the decay rate of HANE electrons. Different scenarios at different phases of the solar cycle or under different geomagnetic conditions can be numerically tested.

3. DREAM RESULTS

We describe here a test case that uses space environment instruments on GPS and geosynchronous satellites to calculate the global, three-dimensional, time-dependent radiation environment. We use an independent set of measurements from a different spacecraft in a completely different orbit to validate the model output.

The data that we assimilate in this example come from the LANL Synchronous Orbit particle Analyzers (SOPA) detectors on three geosynchronous satellites and from the Burst Detector Dosimeter (BDD IIR) on GPS ns41. The data that we use to test and validate our global prediction comes from the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) experiment on NASA's POLAR satellite [*Blake et al.*, 1995]. It is important to emphasize that data from the POLAR satellite are a completely independent set and are not used in the assimilation in any way. Furthermore, POLAR is in a vastly different orbit from the assimilated data sets, i.e. an elliptical orbit with apogee at 9 R_E and perigee at ~1.5 R_E, and inclination of ~80°.

Here we use the flux of 1 MeV electrons measured by POLAR as our test data set and we compare the predictions based on three radiation belt models: DREAM, CRRESELE [*Brautigam and Bell*, 1995], and AE8 [*Vette*, 1991]. Figure 2. shows the results of our calculations for the full year of 2005 when POLAR's orbit provided good observations of the region L>4. The top panel shows the 1 MeV electron fluxes measured by the POLAR satellite (in electrons/cm^2/s/sr/keV). The data are binned into 1-day increments with a spatial resolution of 0.5 R_E in L. The data appear sparse for a variety of reasons including our choice of magnetic parameters μ and K, detector saturation, missing data, etc. The fluxes vary by orders of magnitude both as a function of time and location. As expected, the peak of the electron belt is typically observed between L=4-5 with a steep drop-off in flux at higher L. Fluxes also vary in response to geomagnetic activity (bottom panel). The year 2005 included a number of strong (Dst < -100 nT) and a few intense (Dst < -150 nT) storms.

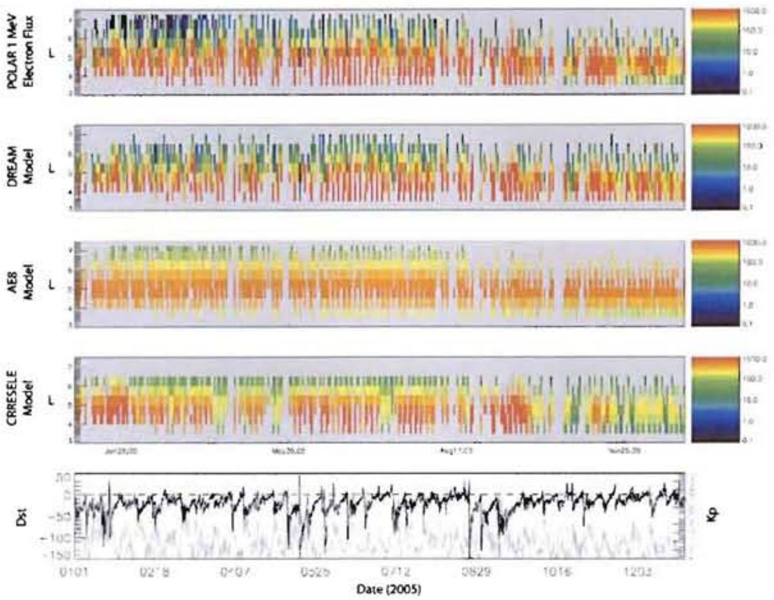

Fig 2. DREAM model results compared with the validation data set from POLAR and the model results from AE8 and CRRESELE.

We have conducted various quantitative validation studies of the results (see *Reeves et al.*, [2008]. The most basic test is the average flux value as a function of equatorial altitude, L. (Geosynchronous orbit is at L=6.6 R_E.) For 2005 the DREAM and CRRESELE averages are within a factor of 2 of the average POLAR across the full range of L. However, AE8 for this interval shows systematic errors and a radial profile that has a very different (flatter) shape. It overestimates fluxes at high L and underestimates fluxes at low L. Where DREAM shows the most improvement over CRRESLELE is in the prediction efficiency (PE) which measures the ability to predict variation around the mean at each time step. DREAM produces positive prediction efficiencies at all L-shells while the other models give a PE ≤ 0 indicating that the variation around the mean is wrong more often than it is right.

4. COSTOM USER INTERFACES

While most of our effort has been on developing accurate predictions of the environment and validating the results, we also anticipate the need to rapidly assess space environment hazards for specific user applications. Therefore we have also been developing a flexible tool kit that can provide the specific information a user needs without confusing or extraneous information. Figure 3 shows prototypes of several tools. The figure is a frame from a movie that displays recent space environment conditions up to a reported anomaly. The upper left shows an orbit visualization calculated from two-line elements in the space catalog. Here we show the DOE satellite, Forté in low Earth orbit. The upper right shows radiation belt intensity as a function of L and time with the Forté orbit superposed and the time of the current frame marked. Below shows flux as a more familiar line plot. Flux, dose, or fluence could be displayed as needed and each quantity could be displayed at a fixed L, as shown here, or along the actual satellite orbit. The lower left shows radiation hazard level based on comparison against the statistical distribution of conditions for that orbit.

In this example the Forté satellite operators can quickly assess that, not only were fluxes low at the time of the anomaly but recent conditions were well within the normal range of conditions seen for that orbit.

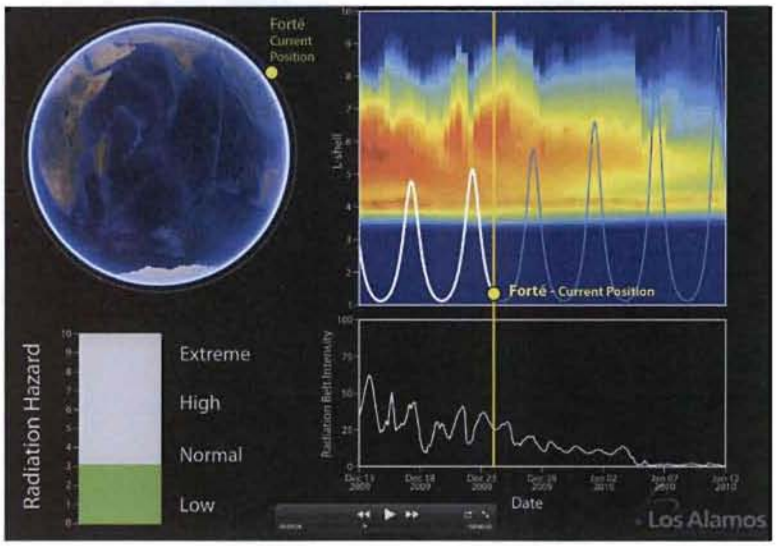

Fig. 3. A set of prototype user tools for assessing hazards from the space environment.

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