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Integration Of Space Weather Into Space Situational Awareness

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ABSTRACT

Rapid assessment of space weather effects on satellites is a critical step in anomaly resolution and satellite threat assessment. That step, however, is often hindered by a number of factors including timely collection and delivery of space weather data and the inherent complexity of space weather information. As part of a larger, integrated space situational awareness program, Los Alamos National Laboratory has developed prototype operational space weather tools that run in real time and present operators with customized, user-specific information. The Dynamic Radiation Environment Assimilation Model (DREAM) focuses on the penetrating radiation environment from natural or nuclear-produced radiation belts. The penetrating radiation environment is highly dynamic and highly orbit-dependent. Operators often must rely only on line plots of 2 MeV electron flux from the NOAA geosynchronous GOES satellites which is then assumed to be representative of the environment at the satellite of interest. DREAM uses data assimilation to produce a global, real-time, energy dependent specification. User tools are built around a distributed service oriented architecture (SOA) which will allow operators to select any satellite from the space catalog and examine the environment for that specific satellite and time of interest. Depending on the application operators may need to examine instantaneous dose rates and/or dose accumulated over various lengths of time. Further, different energy thresholds can be selected depending on the shielding on the satellite or instrument of interest. In order to rapidly assess the probability that space weather was the cause of anomalous operations, the current conditions can be compared against the historical distribution of radiation levels for that orbit. In the simplest operation a user would select a satellite and time of interest and immediately see if the environmental conditions were typical, elevated, or extreme based on how often those conditions occur in that orbit. This allows users to rapidly rule in or out environmental causes of anomalies. The same user interface can also allow users to drill down for more detailed quantitative information. DREAM can be run either from a distributed web-based user interface or as a stand-alone application for secure operations. In this paper we discuss the underlying structure of the DREAM model and demonstrate the user interface that we have developed. We also present some prototype data products and user interfaces for DREAM and discuss how space environment information can be seamlessly integrated into operational SSA systems.

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. DREAM is currently being tested and evaluated as we transition from research to operations.

2. The DREAM NUMERICAL FRAMEWORK

The 2010 Dynamic Radiation Environment Assimilation Model does not consist of a single code or even a single language. DREAM is, in some ways, a computational framework that is extremely flexible and adaptable to new developments, new data sources, and new physical understanding. Code elements in different programming languages are integrated through a common interface based on Python. 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.

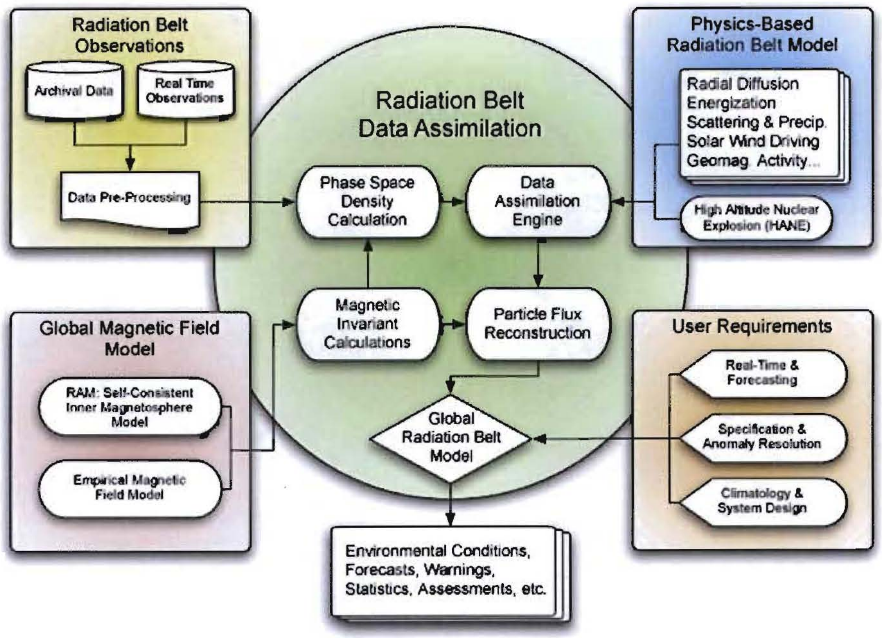

Figure 1: The organizational structure of DREAM is based around a central data assimilation engine using Kalman Filter techniques. Archival or real-time data are preprocessed and transformed into phase space density using magnetic invariants calculated from a global magnetic field module. The Kalman 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.

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 [*Olsen and Pfitzer*, 1974] 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. Fortunatel,y 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 2: 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. DREAM VALIDATION

The "full service" version of DREAM has been tested against independent data sets using spacecraft in different orbits from those that are used in the assimilation. For example we have conducted runs using LANL space environment data from geosynchronous orbit, from one GPS satellite and compared the results against measurements from NASA's POLAR satellite. POLAR was in a high-inclination orbit with ~9 R_E apogee and therefore nothing like the geosynchronous or GPS orbits. We then compared the DREAM output for an entire year (2005) against the CRRESELE and AE-8 models [*Reeves et al.*, 2008]. DREAM not only produces the right average values over L-shells from 3.5 R_E to >7 R_E, it also produces the correct statistical distribution of fluxes. It is even more compelling that the prediction efficiency is consistently positive indicating the ability of the model to correctly predict the temporal variation around the mean values. It is to be expected that data assimilation models will outperform average or statistical models but it is somewhat surprising (and relieving) that a simple physics model with very limited assimilated data could provide the observed level of accuracy for a satellite in a completely different orbit.

4. WEB SERVICES

The DREAM beta web service contains two basic plot types: flux and phase space density. Each plot type is selectable using the tabs above the plot. In either mode, flux or phase space density (PSD) is plotted (using a color-coded scale) as a function of time and radial distance (R) or Drift Shell (L*), both in units of Earth Radii (1 Re = 6370 km). Plots cover approximately 1 month. The plots update automatically every time new data are assimilated. New GOES data is available approximately every 5 min. Status bars at the top of the plot show the status of data availability and progress of the assimilation. It is possible for new data to show up for an earlier time It is also possible for ancillary data such as Kp or calculations of the magnetic invariants to be updated for some time in the past. Progress of recalculating data values is shown in the Data Status bar. Whenever the primary or ancillary data change new assimilations from that time to the present must be calculated and that progress is indicated in the Assimilation Status bar.

When flux (j) is displayed it is in units of particles/(cm^2-s-sr-MeV)$^{-1}$. Six different energies ranging from 1 MeV to 6 MeV are selectable using the pull-down menu below the plot. Five different equatorial pitch angles values ranging from 55° to 75° are also selectable. Each selected energy and pitch angle range returns flux values for a different range of radial distances (R) for reasons described in the procedures and artifacts sections.

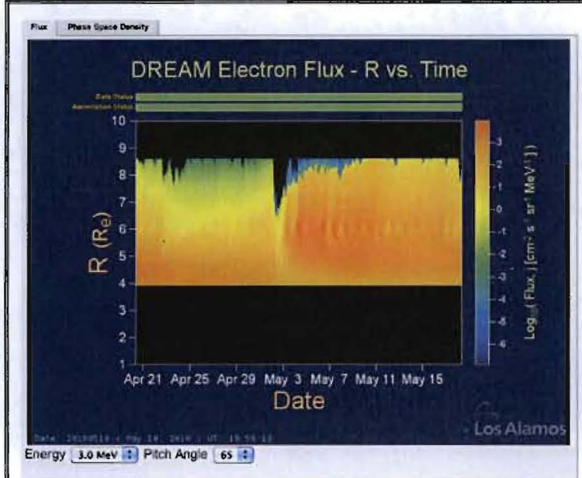

Figure 1: Final DREAM output is flux as a function of equatorial altitude (R) and time. Fluxes for 3 MeV and 65° equatorial pitch angle are shown here but are selectable with the pull down menus just below the plot.

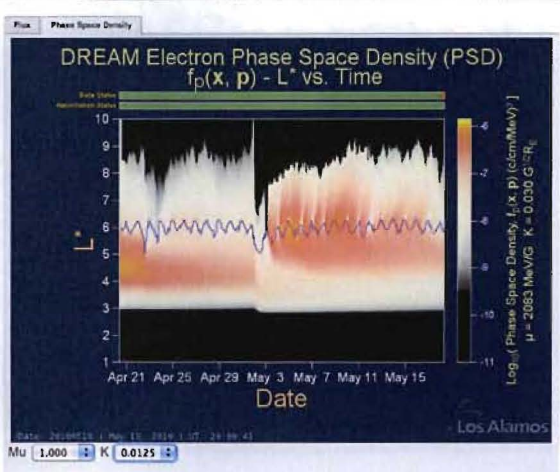

Figure 2: The actual assimilation in DREAM uses phase space density at fixed magnetic invariants (μ, K, L*). Assimilations are done for 25 different μ-K pairs and are visible in the Phase Space Density tab.

When phase space density is displayed it is in units of (c/cm-MeV)^3 for fixed values of the adiabatic invariants, μ, and K. Five different values of μ ranging from 1,000 to 20,000 MeV/G and five different values of K ranging from 0.0125 to 0.20 $G^{1/2}$ R_E are selectable using the pull-down menus. For PSD, DREAM returns valid (but not necessarily accurate) values for all L* from 1 to 10 in 0.1 R_E bins.

Selected space weather parameters such as Kp and Dst are shown in tabular or plot form below the DREAM results. Which parameters are shown may change as we continue to develop the DREAM web service. Similarly the links to the left or right of the plot and the content that those links point to may also vary. Screen shots as of May, 2010 are shown below.

5. PROCEDURES

The DREAM beta web service assimilates data from only a single GOES satellite. We use the NOAA-designated primary GOES satellite which, as of May 2010, is GOES-13. Future versions will assimilate available near-real-time data sources which might include multiple GOES satellites, LANL-GEO, GPS, the RBSP space weather broadcast, and others.

We fit a power law spectrum to the integral GOES energy channels which cover >0.8 MeV and >2 MeV. (Other GOES satellites have channels for >0.6 and >0.2 MeV.) We extrapolate the spectrum to arbitrarily high or low energies as needed. (More physically realistic procedures are certainly possible and errors due to extrapolation are a known limitation.)

The first adiabatic invariant, μ, is calculated from the fit spectrum and the model magnetic field. It is, of course, possible to use the measured GOES magnetic field but the beta version shown here does not. The second invariant, K, is also calculated using the model magnetic field. In calculating phase space density we assume (for the beta version) an isotropic pitch angle distribution.

We calculate the third invariant L* using the [*Tsyganenko*, 1989] model (T89) using the latest Kp values. One effect of using the T89 is a diurnal variation in the L* "position" of GOES. When GOES is on the day side it generally samples lower L* and when it is on the night side it samples higher L*. The specific values of L* also change with activity. At higher activity levels the "Dst effect" inflates the geomagnetic field with the result that lower L* values are sampled.

The plots of PSD show the L* value of GOES with a purple line.

Once we have calculated the magnetic invariants, (μ, K, L) we convert Flux (at fixed energy and pitch angle) to phase space density (PSD). It is actually the PSD values, not the flux values, that are assimilated in the DREAM model. This is because the physics model requires PSD and magnetic invariant coordinates.

The physics model in the DREAM beta web service is a simple radial diffusion model that uses the [*Brautigam and Albert*, 2000] formulation. It includes loss terms for the electron lifetime. Lifetimes are constants inside the plasmasphere and outside the last closed drift shell. Between the plasmapause and the magnetopause the lifetime is Kp dependent. (See [*Shprits and Thorne*, 2004].)

One assimilation is done for each μ-K pair. We currently calculate 25 separate assimilations for five values of μ and five values of K. The assimilations are computationally very fast and there is little trouble in scaling up to 100 or 1,000 assimilations for an operational version.

PSD is calculated for all bins from L* = 1-10. The model seldom produces appreciable PSD inside L*≈3. This is physically realistic and represents the point where inward radial diffusion is slow relative to the electron loss lifetime. We note that while the feature is realistic, the quantitative PSD values are not. We know this from other DREAM assimilation runs that use GPS data as well as geosynchronous data. The GPS observations at L*<5 significantly alter the assimilation results.

The magnetopause defines the limits of trapping for the radiation belts. The L* value of the last closed drift shell is also calculated using the T89 model. While the assimilation space extends to L* = 10, we set a very short electron lifetime outside the last closed drift shell. This creates a "ragged" outer boundary. We know from DREAM runs compared with near-equatorial POLAR observations between geosynchronous orbit and the magnetopause, that the PSD values in that region are generally quite good when realistic input spectra and pitch angle distributions are available.

The final step is to convert back from PSD to flux at fixed energy and pitch angle. At a given point in space different pitch angles have somewhat different L*. Similarly the conversion from μ to energy depends on the local magnetic field which is a function of both radius and local time. Therefore, converting back to flux is strictly possible only for a specified set of points in space. (E.g. along a spacecraft trajectory or a non-Keplerian set of points such as radial distance at fixed local time.) For computational simplicity the beta version here uses the (erroneous) assumption that L* = dipole L = R. Future versions will use the correct conversion procedure.

Conversion from K to equatorial pitch angle is linear. However, the range of pitch angle values in the final product is limited by the range of K values used in the assimilations. The conversion from μ to energy is proportional to the magnetic field strength and is L-dependent. Therefore, the range of L-shells for which flux can be calculated at a given energy and pitch angle is limited by the choice of the range of μ and K values used in the assimilations. As noted above there is no fundamental limit to the number and range of μ and K values that could be computed but, at some point, the extrapolation (in energy or pitch angle) from the omni-directional, integral-energy GOES measurements becomes physically unrealistic. The limitations on final DREAM output are illustrated in the figures below.

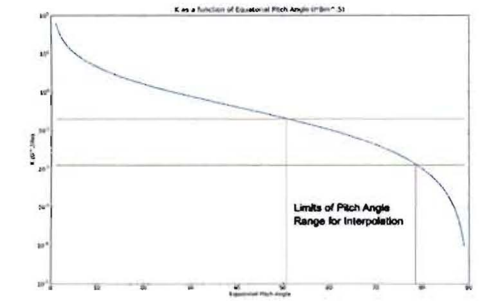

Figure 3: The relationship between the second invariant, K, and equatorial pitch angle α. Values are shown for L* = 6.6 but the relationship does not vary much as a function of L*. The current choice of limiting assimilations to K values between 0.0125 and 0.2 limits the range of equatorial pitch angles we can calculate to between about 50° and 80°. These limits are arbitrary and will be changed in future versions of DREAM

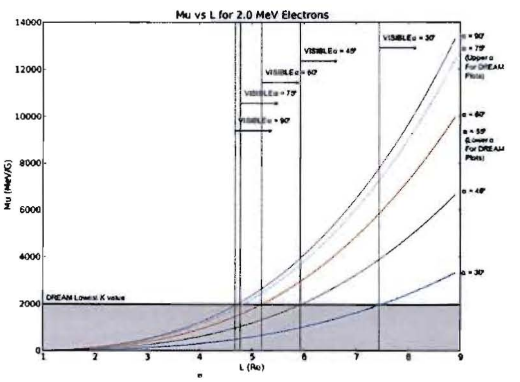

Figure 4: The first invariant is proportional to energy divided by magnetic field strength (E/B) and therefore varies strongly as a function of L*. This plot shows the relationship between μ (Mu) and L* for a fixed energy of 2 MeV and a family of curves for different equatorial pitch angles.

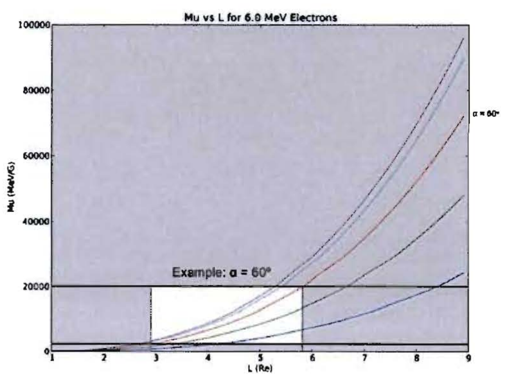

Figure 5: This figure illustrates how a choice of fixed energy and pitch angle imposes limits on the L range in which fluxes can be calculated. This plot shows μ as a function of L* for an energy of 6 MeV. The red curve shows values for a 60° equatorial pitch angle. The heavy black lines show the range of μ values used in the DREAM beta web service (2,000-20,000). The intersection of the red curve with those lines defines the range of L-shells which in this example lie between about 3 and 6 R_E.

6. BETA VERSION: ARTIFACTS AND LIMITATIONS

We have already noted some of the limitations of the DREAM electron flux output. They include:

1. Use of an assumed isotropic pitch angle distribution for the GOES data
2. Limits due to fitting a spectrum to only two GOES integral energy channels
3. A simplifying assumption of dipole L in converting from PSD to flux which is inconsistent with the T89 model L* used when converting the initial flux measurements to PSD.
4. Limits on the range of L-shells for which flux can be calculated. This is due to the limited range of μ and K values chosen for the assimilations

None of these limitations is a fundamental limitation of the DREAM model. The choice of the range of μ and K values can be changed as can the number of μ-K pairs (currently 25). Since a separate assimilation needs to be done for each μ-K pair there are computational limits but it should be possible to increase the range and number of μ and K values significantly while still fitting the computational limitations of a simple desktop computer.

Other limitations and artifacts come from the use of a single satellite as a source of data for the assimilation. Because of the asymmetry of the magnetic field, a geosynchronous satellite at fixed altitude still samples different drift shells (denoted by L*) on the day side and night side of the Earth. This diurnal variation of the L* sampled by GOES is most readily seen in the Phase Space Density plots but ruminants extend to the Flux plots also.

It is almost always true that the phase space density across the range of L-shells sampled by GOES in a single orbit is not constant but, rather, exhibits a radial gradient. When higher PSDs are measured their effects diffuse inward and outward in the model. When lower PSDs are measured their effects also propagate. This often creates "stripes" of higher or lower PSD that propagate to higher or lower L-shells. What it means physically is that radial diffusion cannot reproduce the PSD gradient that exists between the L*-shells measured at noon and midnight. In fact the existence of these artifacts provides important information on the sign and the magnitude of PSD gradients near geosynchronous orbit. We also note that the actual PSD gradients can be a function of μ and/or K and therefore the diurnal artifacts can appear differently for different values of μ and K.

We note that assimilating data from multiple geosynchronous satellites that sample different L-shells simultaneously reduces or eliminates these diurnal artifacts. Two (or more) geosynchronous satellites can measure the PSD gradient directly and include it properly in the model.

The artifacts of diurnal variations can still be seen in the flux data even at energies (i.e. 2 MeV) that were measured in the original input. There are two reasons for this. One is the current mismatch between the magnetic field model used to convert flux to PSD and the field model used to convert back from PSD to flux. The other is more subtle. At any point in space the flux at fixed energy and fixed pitch angle must be reconstructed from interpolated values of discrete μ and K values. Since the artifacts in the PSD calculations can be different for different μ-K pairs and the flux at any given time and location needs to interpolate between different μ and K values, the artifacts do not "cancel out".

Future versions of the DREAM web services will use the same magnetic field model in all calculations. Some artifacts will remain if flux is calculated at an arbitrary position but if we calculate flux at the location of the input GOES data we should be able to reproduce the original measurements with high accuracy. A measure of this accuracy tests the numerics but also tests the effects of spectral fitting or the assumption of isotropic pitch angle distributions.

It is also possible to use a single GOES satellite as input and a different GOES satellite as a validation data set. Using the LANL-GEO observations we assimilate multiple geosynchronous satellites (reducing diurnal artifacts) and still have one or more geosynchronous satellites for validation. With proper validation data sets we can quantitatively test the errors introduced by different simplifying assumptions or by limited data availability.

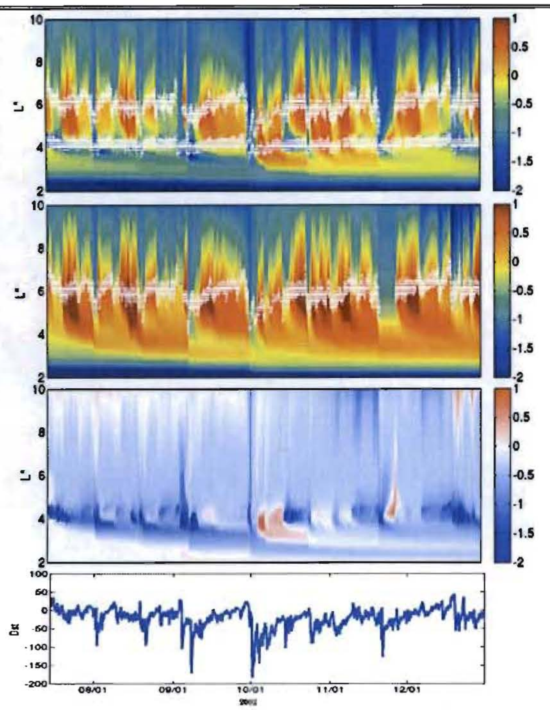

Figure 6: This figure shows PSD values from the DREAM assimilation using geosynchronous and GPS observations (top) and compares it with an assimilation using only geosynchronous observations (panel 2). The remaining panels show the ratio of PSD values obtained from the two model runs, and the Dst index. This figure is illustrative of the types of tests that can be conducted to determine where and when the models perform best. Similar tests can quantify the uncertainties (or errors) in the model as a function of energy, pitch angle, spatial location, and/or geomagnetic activity. Such studies will be conducted in the near future.

An example of one quantitative test using PSD values is shown in the figure above. In the top panel we have used three geosynchronous satellites and one GPS satellite in the assimilation. We show near-equatorial K values which GPS samples only close to 4 R_E. In the second panel we conduct the same assimilation with the same assumptions but without GPS observations. Next we show the ratio of the two assimilation results for this μ-K pair on a log scale. Geomagnetic activity (Dst) is plotted in the bottom panel. As we can see, using geosynchronous observations alone produces PSD values that can be too high by a factor of 100 or too low by a factor of 10.

We have done similar tests for larger K values (which also extends the L* range of available GPS observations) and found that using geosynchronous data alone generally produces the largest errors inside $L \approx 5$. We have also done similar comparisons of assimilations with and without POLAR observations outside geosynchronous orbit and find that the assimilations reproduce PSD values outside geosynchronous orbit surprisingly well.

It is important to note that true validation should be done on flux values rather than on PSD values. These initial comparisons are illustrative of what *could* be done and where the largest errors are expected. Some initial, quantitative validations of fluxes from DREAM has been published in the AMOS conference proceedings [*Reeves et al.*, 2008].

The DREAM beta web service also has limitations on times that are available. The beta web service was developed specifically for real time data and real time specifications (nowcasts). This means that it is not currently simple to request a specific period of time or to store a database of values that spans many years. We are currently re-working the codes in order to make it possible to run a DREAM assimilation for a user-selectable period of time and a user-selectable set of available satellite data sets as either input or validation. We are currently working with the Air Force Space Weather Forecast Laboratory (SWFL) and NASA's Community Coordinated Modeling Center (CCMC) to perform more extensive validations once the greater flexibility is available.

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