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Radiation belt electron flux forecasts: Driving VERB using NARMAX GSO flux forecasts

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ABSTRACT

Physics based models, such as VERB, are capable of achieving excellent past-cast and now-cast models of the dynamics of electron fluxes throughout the radiation belt region. Their ability to forecast, however, is strongly dependent upon the accurate forecast of their driving parameters. In contrast, data based models, generated using Systems Science methodologies such as NARMAX, have been shown to achieve highly accurate forecasts over limited spatial domains such as GSO. This paper outlines the use of NARMAX forecasts to drive VERB. Example past-casts are discussed and compared to observations from the Van Allen Probe MagEIS instrument.

INTRODUCTION

There are two general methodologies typically used in the modeling of radiation belt processes, namely those built upon physical principles and empirical models that rely on the analysis data.

Physical models

Physical models of a system rely on our knowledge and understanding of the processes occurring within a system. The complete system is broken down into a set of processes that we know or suspect are occurring within the system. A model for each process is then formulated, based on a physical description of that processes, often with some underlying, simplifying assumptions. The model descriptions for these individual processes are then concatenated, outlining the complete chain of events that operate within the system. The results may then be compared to observations of the system in order to quantify the accuracy of the model. Differences between the model output and observations indicate that either some of the underlying assumptions are not true or that there are processes occurring that have not been included within the model. Typical examples include VERB, PADIE.

Empirical models

In contrast, empirical models are based on the analysis of observations. Typical methods used include the use of

- Moving average linear filters e.g. the prediction of the flux of >2MeV electrons based on the Kp index [Nagai, 1988]
- Linear prediction filters e.g. estimation of the fluxes of high energy electrons based on Kp, AE, and the solar wind velocity [Baker et al., 1990, Vassiliadis et al., 2002],
- Neural networks [e.g. Koons and Gorney, 1991, Fukata et al, 2002, Ling et al, 2010]
- Analysis of radial diffusion coefficients [Li et al, 2001]
- Dynamical nonlinear time series analysis + conditional probability of solar wind + magnetospheric inputs [Ukhorskiy et al., 2004]
- The time delay between observations of flux increases at different energies [Turner and Li, 2008]
- Analysis of flux probability distributions [Denton et al, 2015]
- Probability distributions of solar wind parameters [Kellermann et al, 2013]
- Application of systems analysis methodologies e.g. NARMAX [Boynton et al., 2013]

In all cases the resulting model will be able to provide a set of forecasts to model the evolution of the system, based on the driving parameters used in the analysis. However, only the latter technique is capable of providing a interpretable model that can provide physical insight into the processes occurring.

This poster describes a new model, VNC, that is hybrid of two models, one a physical model (VERB) driven by data from an empirical based NARMAX model. The resulting model thus combines the strengths of each model to overcome the weaknesses of the other.

Comparison of Physical and systems based models

These two modeling methodologies have their own sets of advantages and disadvantages.

- Physical models require a complete knowledge of all processes occurring within a system to provide accurate results whereas in the case of systems models there is often minimal knowledge of the system available.
- Physical models require driving parameters to describe the level of geomagnetic activity (e.g. Kp, Dst, AE) together with the definition of boundary conditions e.g. electron fluxes. In contrast, empirical and systems based models require constant streams of input data for model training, validation, and testing.
- Physical models of the radiation belts are capable of modeling electron fluxes within the whole region of the radiation belts where as empirical models are limited to locations with a high density of data such as Geosynchronous Earth Orbit
- Physical models tend to result in lower accuracy predictions. Systems models are currently the most accurate.

VERB

VERB, the Versatile Electron Radiation Belt model [Subbotin et al, 2011] is a diffusion code that models radiation belt particle dynamics using the bounce averaged Fokker-Planck equation with radial, pitch angle, energy, and mixed diffusion terms.

$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\bigg|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\bigg|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\bigg|_{\alpha_0,L}\cdot p^2\left(D_{pp}\frac{\partial}{\partial p}\bigg|_{\alpha_0,L} f + D_{p\alpha_0}\frac{\partial}{\partial \alpha_0}\bigg|_{p,L} f\right)$$
$$+ \frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\bigg|_{p,L}\cdot T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\bigg|_{p,L} f + D_{\alpha_0 p}\frac{\partial}{\partial p}\bigg|_{\alpha_0,L} f\right) + \frac{f}{\tau}$$

where f is the electron phase space density, p is the relativistic momentum, α_0 is the equatorial pitch angle, and L^* is the Roeder parameter, μ, J, and φ refer to the first, second and third adiabatic invariants, $T(\alpha_p)$ is a function related to the bounce frequency, and τ is the quarter of the bounce period inside the loss cone describing atmospheric losses.
The occurrence of plasma wave modes (such as chorus, hiss, and magnetosonic waves) has been shown to locally modify the electron distribution function, either by accelerating particles to high energy or scattering particles into the loss cone. VERB takes account of these processes by incorporating sets of diffusion tensors, calculated from the wave amplitudes generated by statistical wave models.
As inputs, VERB requires values of

- Kp geomagnetic index to characterise the current geomagnetic activity
- The electron boundary flux to characterise the inflow of particles from the geomagnetic tail.

The output from VERB is an array of electron phase space densities PSD array as a function of L*, energy, pitch angle and as a function of adiabatic invariant.

NARMAX

NARMAX (Nonlinear AutoRegressive Moving Average with eXogenous inputs) is a modeling framework originally developed in the field of system science [Billings et al., 1989]. It provides a basis for the temporal or spatio-temporal modeling of complex, unknown systems. It has since been applied in many areas of science and engineering from neuroscience and synthetic biology, financial systems, machine vision, object tracking, as well as space physics.

NARMAX represents the system as

$$y(k) = F[y(k-1),\ldots,y(k-ny),u(k),\ldots,u(k-nu),e(k-1),\ldots,e(k-ke)]$$

where $y(k)$ are the system output measurements at time k, $u(k)$ are the system input measurements at times k, $e(k)$ are the noise/error terms at time k, and F[] is a nonlinear function (polynomial, B-spline, radial basis function). Thus, as well as taking into account the current measurements of the system, NARMAX also incorporates its recent history.

VNC – VERB-NARMAX-Coupled model

The VERB-NARMAX-Coupled model (VNC) attempts to integrate these two different yet complementary approaches for past/fore-casting purposes. An initial study was performed by Pakhotin et al, [2014].

NARMAX models are used to estimate the fluxes of electrons in the energy ranges E>2MeV and E>800keV at GSO, and hence to compute the boundary flux required by VERB. These models have been operating in Sheffield since March 2012 and their results can be accessed using the URL http://ssg.group.shef.ac.uk/ssg2013/proj_UOSSW.htm.

The 1 day ahead forecasts of electron fluxes from these models has recently been compared to that of REFM at NOAA [Balikhin et al., 2016] using GOES 13 measurements as a baseline. This study concluded that the NARMAX models routinely had a higher prediction efficiency and correlation than REFM and also showed superior Heidke skill scores for periods when extreme fluxes were observed.

The NARMAX forecast of electron fluxes in the energy ranges >2Mev and >800keV at GSO (~L=6.6) are used to estimate the electron boundary flux required by VERB (900 keV at L^* = 7).

The second input required by VERB is Kp. Currently this is downloaded from the OMNI-web data site http://omniweb.gsfc.nasa.gov/ since the system is currently used for past-casts. This part of the model is currently being redeveloped to retrieve current values of Kp from GFZ, Potsdam ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap together with Kp forecasts from the Wing model at ftp://ftp.swpc.noaa.gov/pub/lists/wingkp and other forecasts that will soon be available from the Horizon 2020 funded PROGRESS project.

Figures 1-4 show an example past-cast using VNC. The period shown corresponds to the St. Patrick's Day storm (March 17, 2015). Figure 1 shows the NARMAX electron flux forecasts (red) for energies >2MeV (solid) and >800keV (dashed). For comparison, the measured GOES 13 fluxes for this period are shown in blue. The Prediction Efficiencies and Correlation coefficients are shown in Table 1.

Figure 2 shows the values of Kp during this period (dotted), along with the VERB estimated plasma pause position (solid). During this storm Kp reached a maximum level of 7, indicating a large geomagnetic storm took place.

Table 1: Prediction efficiencies and correlation of NARMAX flux estimates

	>2 MeV	>800 keV
PE	0.83	0.76
Corr	0.93	0.93

Figure 3 shows measurements of the flux of electrons with energies ~900keV. The measurements show a sudden deletion in the electron population for all distances L^* followed by highly intense electron fluxes.

Figure 4 shows the results from the VNC model. The intensification of the flux is reproduced extremely well. However, the dropout experienced prior to this is not so well reproduced. This is probably related to the fact that the NARMAX electron fluxes shown in Figure 1 fail to predict the dropout.

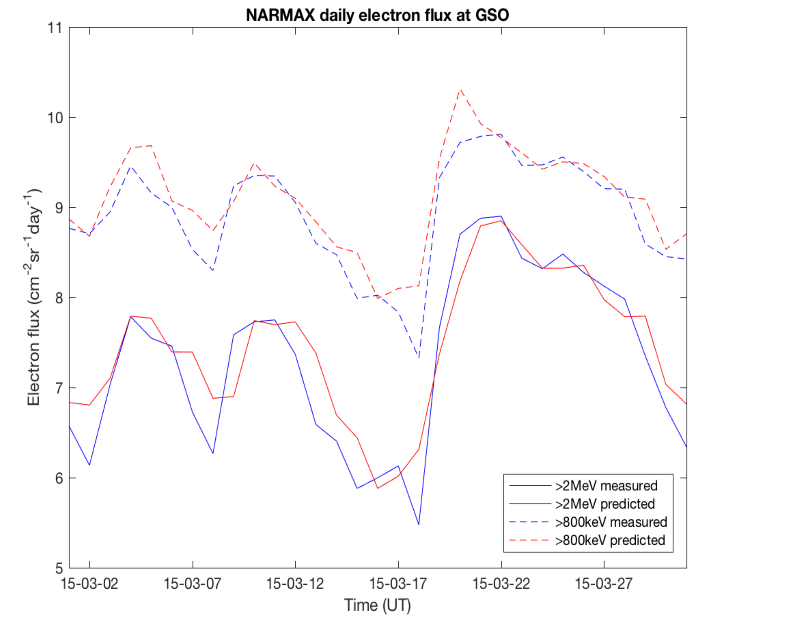

Figure 1: A comparison of the NARMAX forecasts of energetic electron fluxes with measurements from GOES 13.

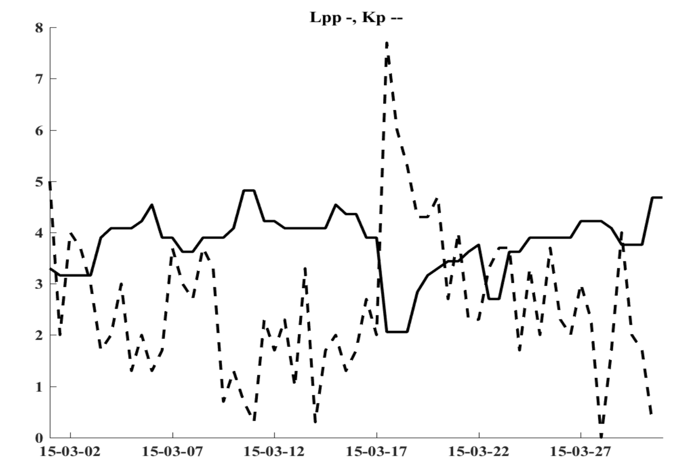

Figure 2: Model plasmapause location Lpp (solid line) and Kp variation (dashed line)

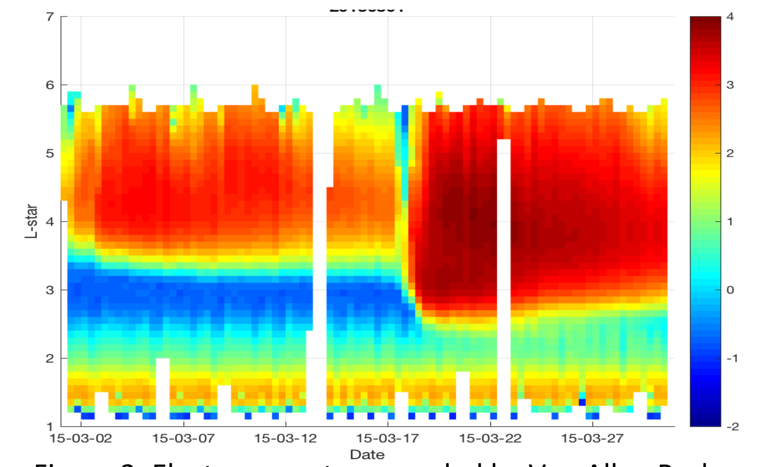
Figure 3: Electron spectra recorded by Van Allen Probes MagEIS instrument

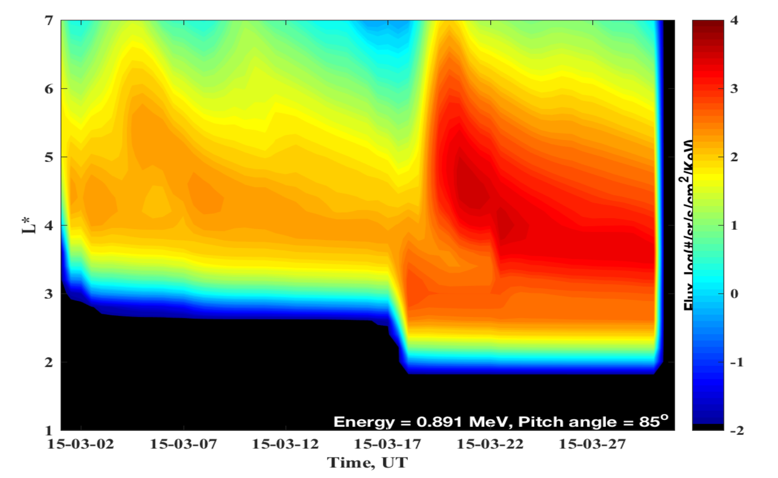

Figure 4: Output from VNC

FUTURE DEVELOPMENTS

Under development

- Current (preliminary) Kp values from GFZ, Potsdam
- Forecasts of Kp
  - Wing model
  - Sheffield, Lund (EU funded project PROGRESS)
- Quantitative comparison with experimental data

Future plans

- Transfer system to the PROGRESS web site (https://ssg.group.shef.ac.uk/progress/html/)

SUMMARY

Coupling of the VERB first principles and NARMAX systems models

- NARMAX was used to forecast daily fluxes of >800keV and >2Mev electrons at GEO
- These fluxes were used to estimate the input boundary fluxes for VERB
- VERB was then used to simulate the electron fluxes
- Qualitatively, the results reproduce measurements from the Van Allen Probes MagEIS instrument during periods of enhanced activity

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