PROGRESS

Use of systems based models for the forecasting of space weather

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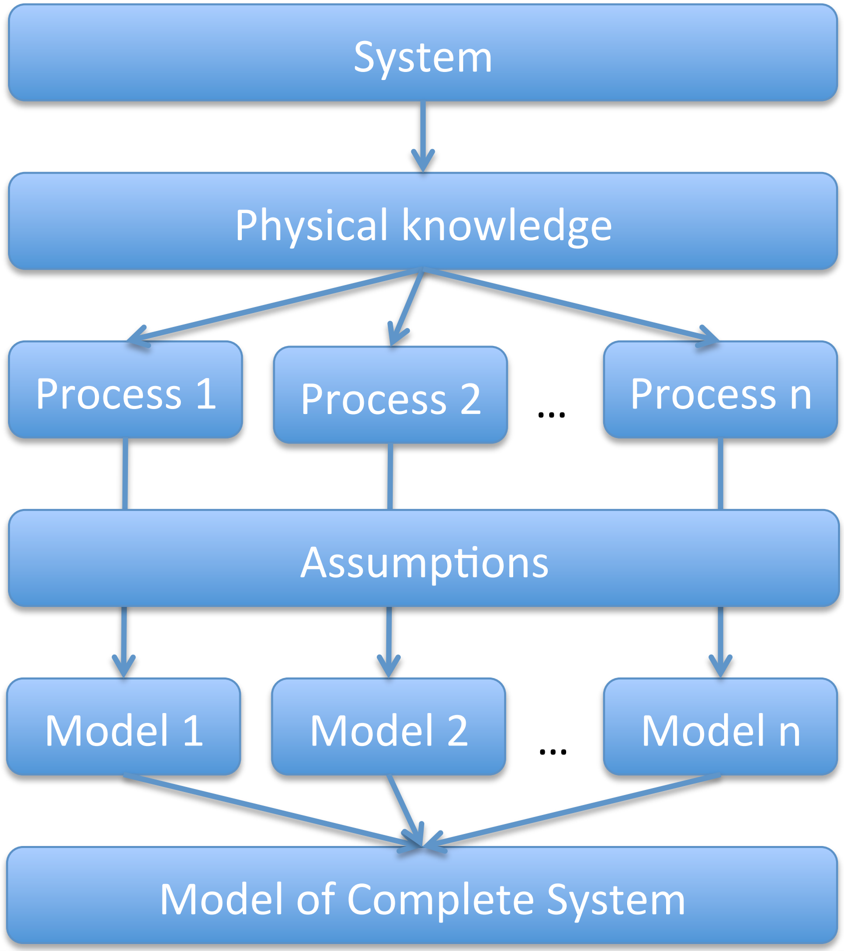
Overview

- Modeling methodologies
- NARMAX modeling
  - Kp
  - Electron fluxes at GEO
  - Electron dropout events

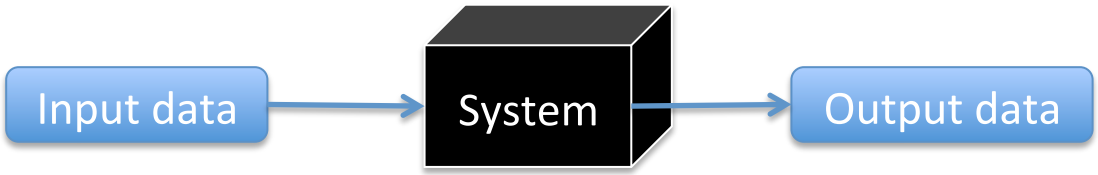
Modeling Methodologies

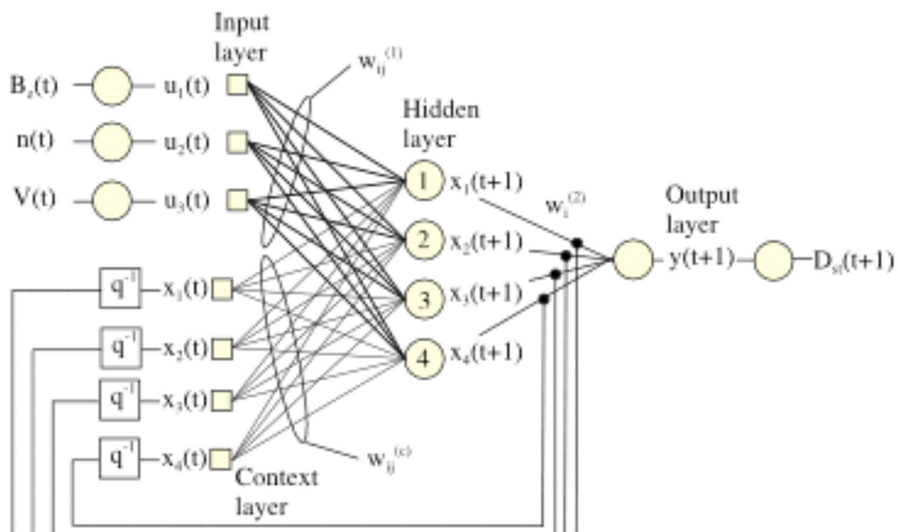
First principles, physics based models



Modeling Methodologies

Neural Network Approach

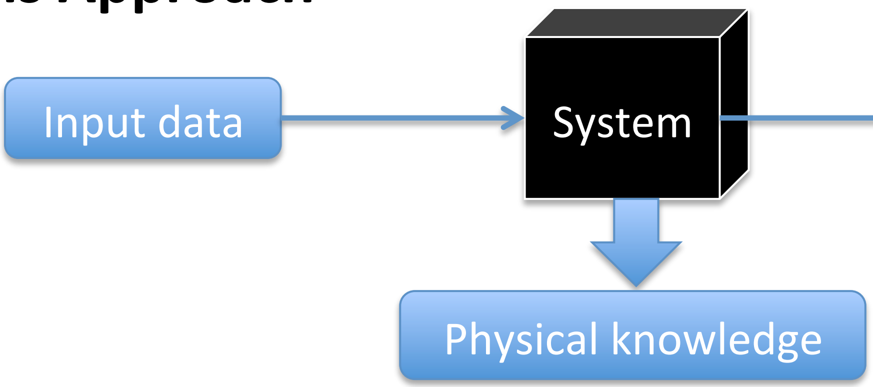




Peter Wintoft, 2002.

Modeling Methodologies

Systems Approach



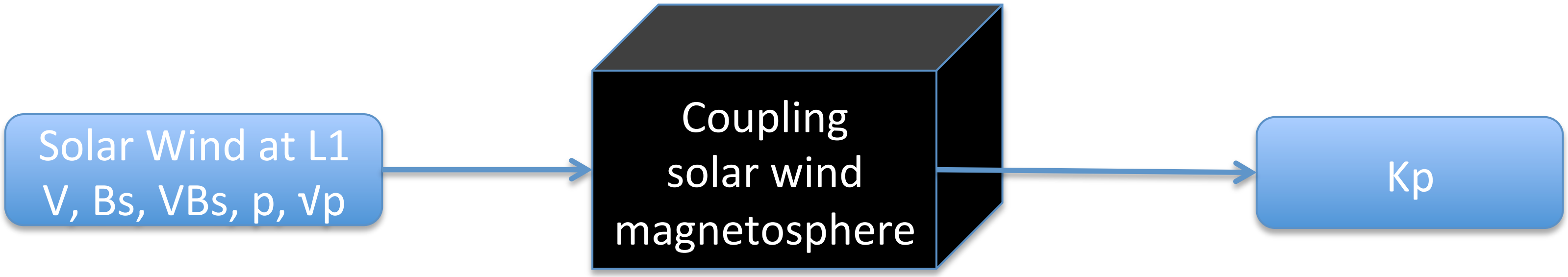
$$y(k) = F[y(k-1),\ldots,y(k-ny),$$ System outputs

$$u(k),\ldots u(k-nu),$$ System inputs

$$e(k-1),\ldots e(k-ne)]$$ Noise/errors

F[] is a nonlinear function (polynomial, B-spline, radial basis function)

Kp



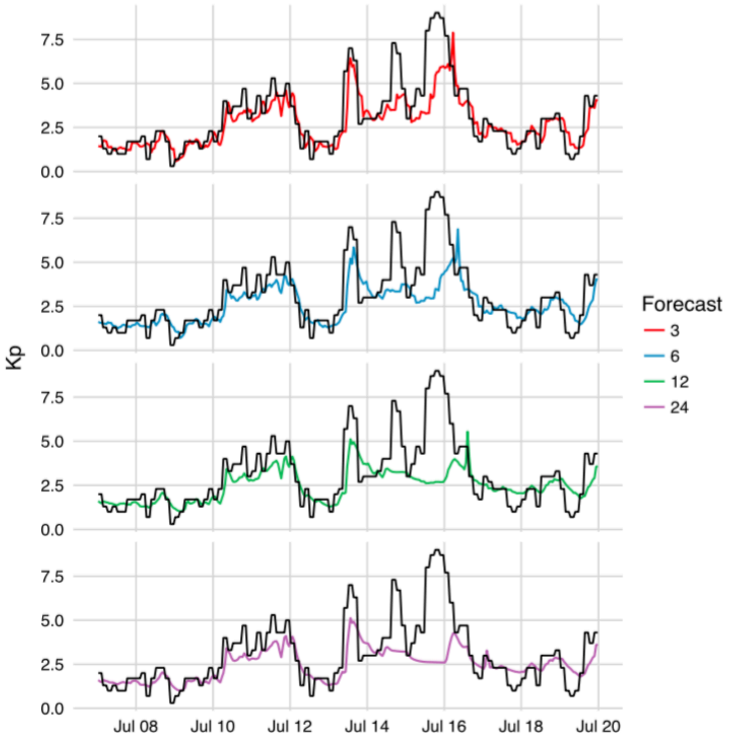
Two approaches

- Sliding window
  - Used to forecast 3, 6, 12, 24h ahead
  - Fixed length window to build model
  - Window moved 1 time step
  - Repeat
- Direct approach
  - One model for each forecast horizon
  - Trained Jan-Jun 2000
  - Validate Jul-Dec 2000

Ayala Solares, J. R., et al. (2016), Modeling and prediction of global magnetic disturbance in near-Earth space: A case study for *Kp* index using NARX models, *Space Weather*, *14*, 899–916, doi: 10.1002/2016SW001463

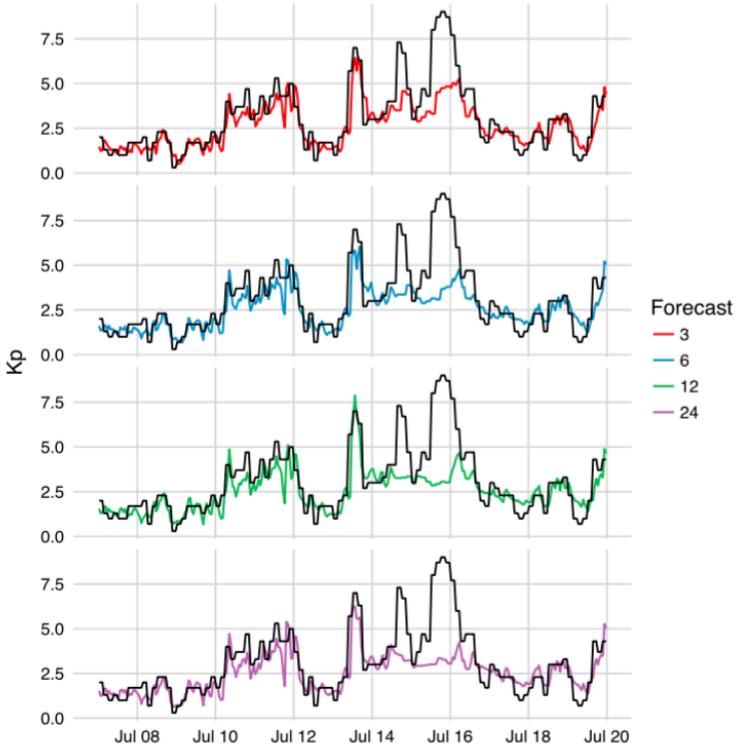
Kp

Sliding window models



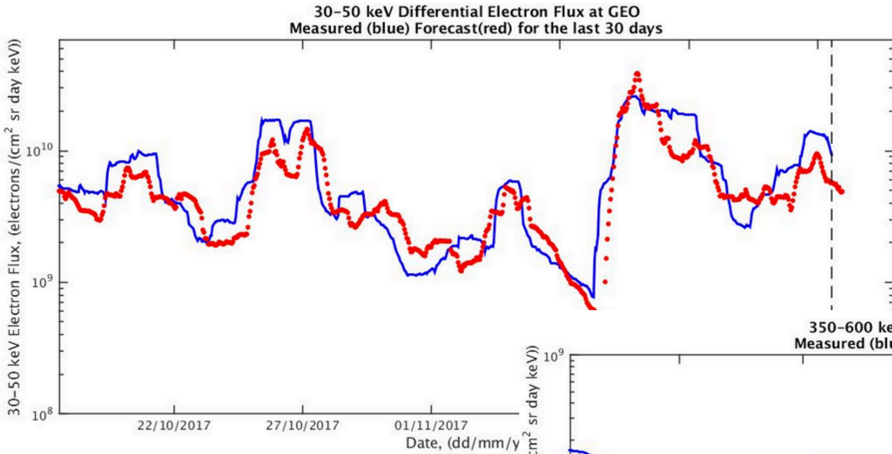
Horizon	RMSE	ρ	PE
3	0.7935	0.8590	0.7359
6	0.9014	0.8159	0.6598
12	0.9513	0.7991	0.6225
24	0.9624	0.7972	0.6149

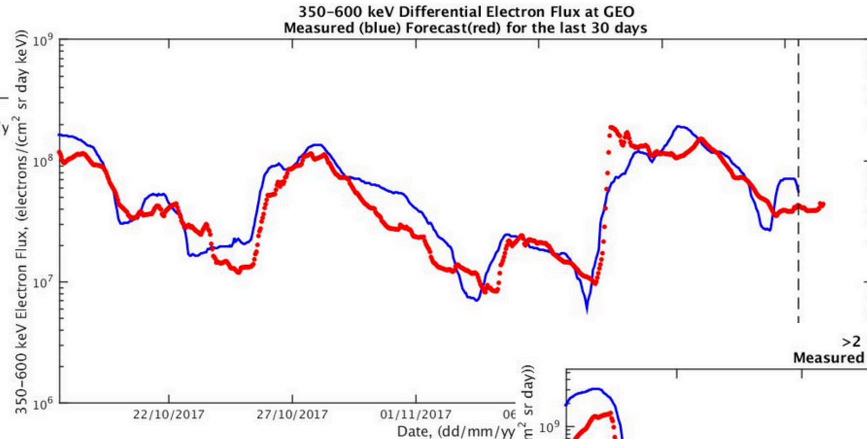
Direct models

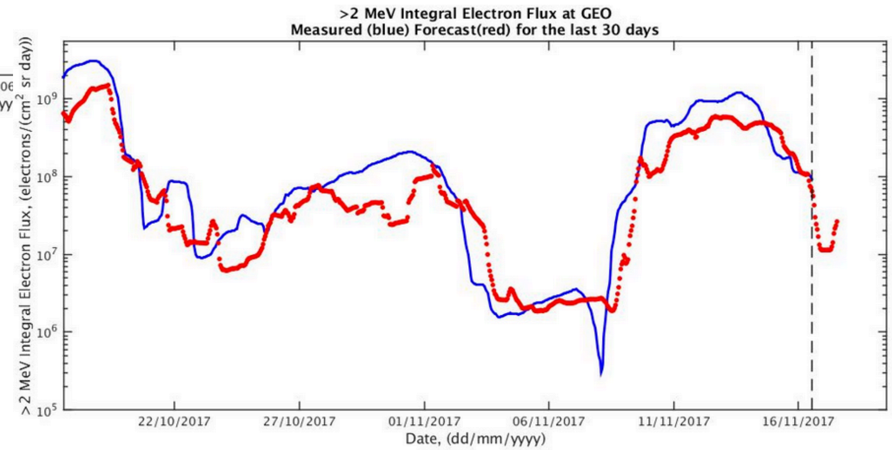


Horizon	RMSE	ρ	PE
3	0.7593	0.8711	0.7585
6	0.8328	0.8424	0.7096
12	0.8623	0.8305	0.6895
24	0.8719	0.8265	0.6824

GSO e⁻ flux forecasts







Models for

- 30-50 keV,
- 50-100 keV
- 100-200 keV,
- 200-350 keV,
- 350-600 keV,
- >800 keV,
- >2MeV

View latest forecasts at
https://ssg.group.shef.ac.uk/progress/html/
http://ssg.group.shef.ac.uk/ssg2013/proj_UOSSW.htm

GSO e^- flux forecasts

Model comparison

One day ahead forecasted fluxes >2 MeV electrons compared with NOAA REFM

Prediction Efficiency

$$PE = 1 - \frac{1}{N}\sum \frac{(X_i - Y_i)^2}{\mathrm{Var}(X)}$$

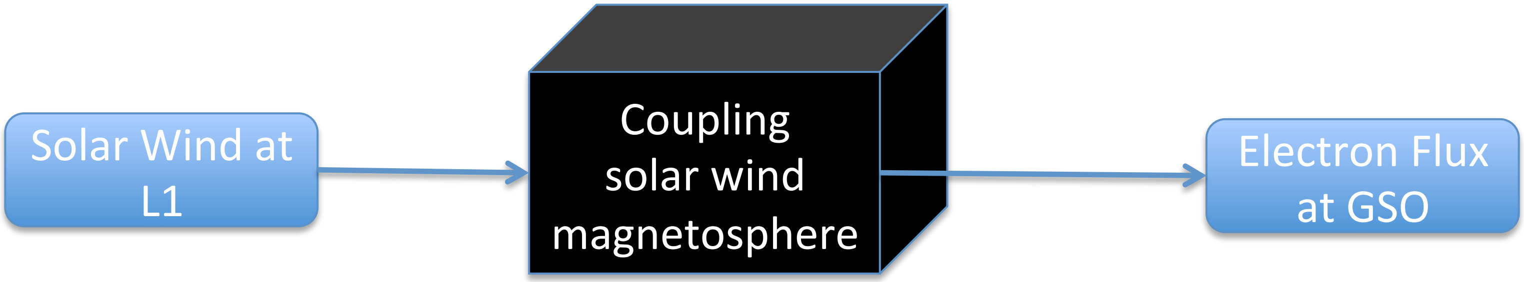
Correlation function

$$C_{\log(SNB)} = \frac{1}{N}\sum_{i=1}^{N} \frac{(\log_{10}(F_{2MeV}(i)) - \langle \log_{10}(F_{2MeV}(i))\rangle)(\log_{10}(F_{SNB}(i)) - \langle \log_{10}(F_{SNB}(i))\rangle)}{\sqrt{\mathrm{Var}(\log_{10}(F_{2MeV}))\mathrm{Var}(\log_{10}(F_{SNB}))}}$$

	e^- Flux		Log10(e^- Flux)	
Model	PE	Corr	PE	Corr
REFM	-1.31	0.73	0.70	0.85
SNB^3GEO	0.63	0.82	0.77	0.89

Balikhin, M. A., et al. (2016), Comparative analysis of NOAA REFM and SNB3GEO tools for the forecast of the fluxes of high-energy electrons at GEO, *Space Weather*, *14*, 22–31, doi:10.1002/2015SW001303.

Electron Fluxes at GSO



Energy	Term 1	%ERR	Term 2	% ERR
90 keV	V(t)	97.0	$V^2(t)$	2.7
127.5 keV	V(t)	74.8	V(t-1)	22.2
172.5 keV	V(t-1)	65.7	V(t)	31.6
270 keV	V(t-1)	97.5	$V^2(t-1)$	2.3
407.5 keV	V(t-1)	84.1	V(t-2)	13.7
625 keV	V(t-1)	75.9	V(t-2)	22.3
925 keV	V(t-2)	96.2	N(t)	0.3
1.3 MeV	$V^2(t-2)$	76.5	nV(t-1)	2.2
2.0 MeV	N(t-1)	53.7	nV(t-1)	13.6
1.8-3.5 MeV	N(t-1)	51.5	$N^2(t-1)$	15.1

Boynton, R. J., et al., (2013), The analysis of electron fluxes at geosynchronous orbit employing a NARMAX approach, J. Geophys. Res. Space Physics, 118, 1500–1513, doi: 10.1002/jgra.50192.

Electron Flux dropouts

Which solar wind parameters/geomagnetic indices control the drop out of electron fluxes ?

L=4.2 (GPS orbit)

Energy	1^{st} Term	ERR
120 keV	$p(t-2)Dst(t-4)B_s(t-1)$	10.55
210 keV	$p(t-2)Dst(t-4)B_s(t-1)$	3.806
300 keV	$p(t-2)Dst(t-4)B_s(t-1)$	0.199
425 keV	$p(t-0)^2Dst(t-0)$	0.1808
600 keV	$p(t-0)^2Dst(t-0)$	6.566
800 keV	$B_s(t-1)^3$	36.71
1 MeV	$B_s(t-1)^3$	54.37
1.6 MeV	$B_s(t-1)^3$	61.08
2 MeV	$B_s(t-1)^3$	61.22
3 MeV	$B_s(t-1)^3$	61.24
4 MeV	$B_s(t-1)^3$	61.07
5 MeV	$B_s(t-1)^3$	61.27
6 MeV	$B_s(t-1)^3$	61.29
8 MeV	$B_s(t-1)^3$	61.1
10 MeV	$B_s(t-1)^3$	61.1

R. J. Boynton,1 D. Mourenas,2 M. A. Balikhin,1, Electron flux dropouts at L ~ 4.2 from Global Positioning System satellites: Occurrences, magnitudes, and main driving factors Accepted J. Geophys. Res. (Space Physics), 10.1002/2017JA024523

L=6.6 (GEO orbit)

Energy	First Term
24 keV	$AE(t-1)$
31 keV	$AE(t-1)$
42 keV	$AE(t-1)$
63 keV	$AE(t-2)n(t-1)$
90 keV	$AE(t-2)n(t-1)$
128 keV	$p(t-1)n(t-0)$
173 keV	$p(t-1)n(t-0)$
270 keV	$p(t-1)n(t-0)$
408 keV	$p(t-1)n(t-0)$
625 keV	$p(t-1)n(t-0)$
925 keV	$p(t-1)n(t-0)$
1.3 MeV	$p(t-0)B_s(t-1)$
2 MeV	$p(t-1)B_s(t-1)$
2.7 MeV	$p(t-1)n(t-0)$

Boynton, R. J., D. Mourenas,and M. A. Balikhin (2016), Electron flux dropouts at Geostationary Earth Orbit: Occurrences, magnitudes,and main driving factors, *J. Geophys. Res. Space Physics*, *121*, 8448–8461, doi: 10.1002/2016JA022916.

Coupling functions

Many solar wind-magnetosphere coupling functions have been proposed

Name	Coupling Function	Reference
I_B	VB_s	*Burton et al.* [1975]
ε	$VB^2 \sin^4(\theta/2)$	*Perreault and Akasofu* [1978]
I_W	$VB_T \sin^4(\theta/2)$	*Wygant et al.* [1983]
I_{SR}	$p^{1/2} VB_T \sin^4(\theta/2)$	*Scurry and Russell* [1991]
I_{TL}	$p^{1/2} VB_T \sin^6(\theta/2)$	*Temerin and Li* [2006]
I_N	$V^{4/3} B_T^{2/3} \sin^{8/3}(\theta/2)$	*Newell et al.* [2007]
I_V	$n^{1/6} V^{4/3} B_T \sin^4(\theta/2)$	*Vasyliunas et al.* [1982]

NARMAX was used to determine the top 5 coupling functions

- 7 function + Dst
- time lags (t-1), …, (t-5)

Coupling Function	NERR (%)
$p^{1/2} VB_T \sin^6(\theta/2)(t-1)$	31.32
$VB_s(t-1)$	12.76
$n^{1/6} V^{4/3} B_T \sin^4(\theta/2)(t-1)$	10.30
$p^{1/2} VB_T \sin^4(\theta/2)(t-1)$	8.37
$D_{st}(t-2)$	7.23

Top 5 sets of parameters $p^{1/2}$, $n^{1/6}$, V, $V^{4/3}$, B_s, $B_T\sin^4(\theta/2)$ and $B_T\sin^6(\theta/2)$ combined by NARMAX

Coupling Function	NERR (%)
$p^{1/2} V^{4/3} B_T \sin^6(\theta/2)(t-1)$	5.46
$p^{1/2} V^2 B_T \sin^6(\theta/2)(t-1)$	3.18
$n^{1/6} V^2 B_T \sin^4(\theta/2)(t-1)$	3.15
$D_{st}(t-2)$	2.96
$p^{1/2} VB_T \sin^6(\theta/2)(t-1)$	2.77

Balikhin, M. A. et al. (2010), Data based quest for solar wind-magnetosphere coupling function, Geophys. Res. Lett., 37, L24107, doi:10.1029/2010GL045733

Summary

In the presentation it has been shown that the systems methodology NARMAX may be used to

- Generate data based models for the forecast of space weather related parameters
- Provide some insight in to the physical processes occurring within the system

Thank you for your attention

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637302.