Understanding the radiation environment in the Earth's inner magnetosphere

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and SPACESTORM and PROGRESS teams

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4th Cluster and THEMIS workshop, 7-12 November 2016, Palm Springs, CA, USA

EU FP7 SPACESTORM project overview
http://www.spacestorm.eu/

SPACESTORM is a collaborative Project funded by the European Union's 7th Framework Programme to model space weather events and mitigating their effects on satellites.
The project builds on the forecasting of space weather started by the FP7 SPACECAST project.

The SPACESTORM consortium consists of five partners:
(1) Natural Environment Research Council – British Antarctic Survey (NERC-BAS), UK
(2) Ilmatieteen Laitos (FMI, Finnish Meteorological Institute), Finland
(3) DH Consultancy BVBA (DHC), Belgium
(4) University of Surrey – Surrey Space Centre (SSC), UK
(5) Office National D'Etudes et de Recherches Aerospatiales (ONERA), France

Goal
To model severe space weather events and mitigate their effects on satellites by developing better mitigation guidelines, forecasting, and by experimental testing of new materials and methodologies to reduce vulnerability.

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Modelling of 30 years of radiation belts

- BAS Radiation Belt Model: diffusion equation for the drift averaged phase-space density, includes (1) Radial transport, (2) Wave-particle interactions (Plasmaspheric hiss, Lightning generated whistlers, Upper band, lower band and low-frequency chorus, EMIC waves), (3) Loss to the atmosphere, (4) Loss to the magnetopause.

- >2 MeV electron flux from GOES provides outer boundary condition

Model requires whole energy spectrum at a fixed L*
Data provides one integral energy at varying L* (diurnal variation)

- Asynchronous regression [O'Brian et al., 2001] removes diurnal variation
  - Maps the flux measurement at any MLT, to the flux that would be measured by the same instrument at a fixed, reference local time
  - So the >2MeV flux is mapped to a fixed L*

- Use activity dependent spectra fitted at >2MeV to get whole spectrum
  - Developed a set of spectra from 150keV, 275 keV, 475 keV, >800 keV and >2 MeV channels on GOES 15
  - Use these to get spectrum at fixed L* from the mapped >2MeV flux

30 years simulation

Long term variability

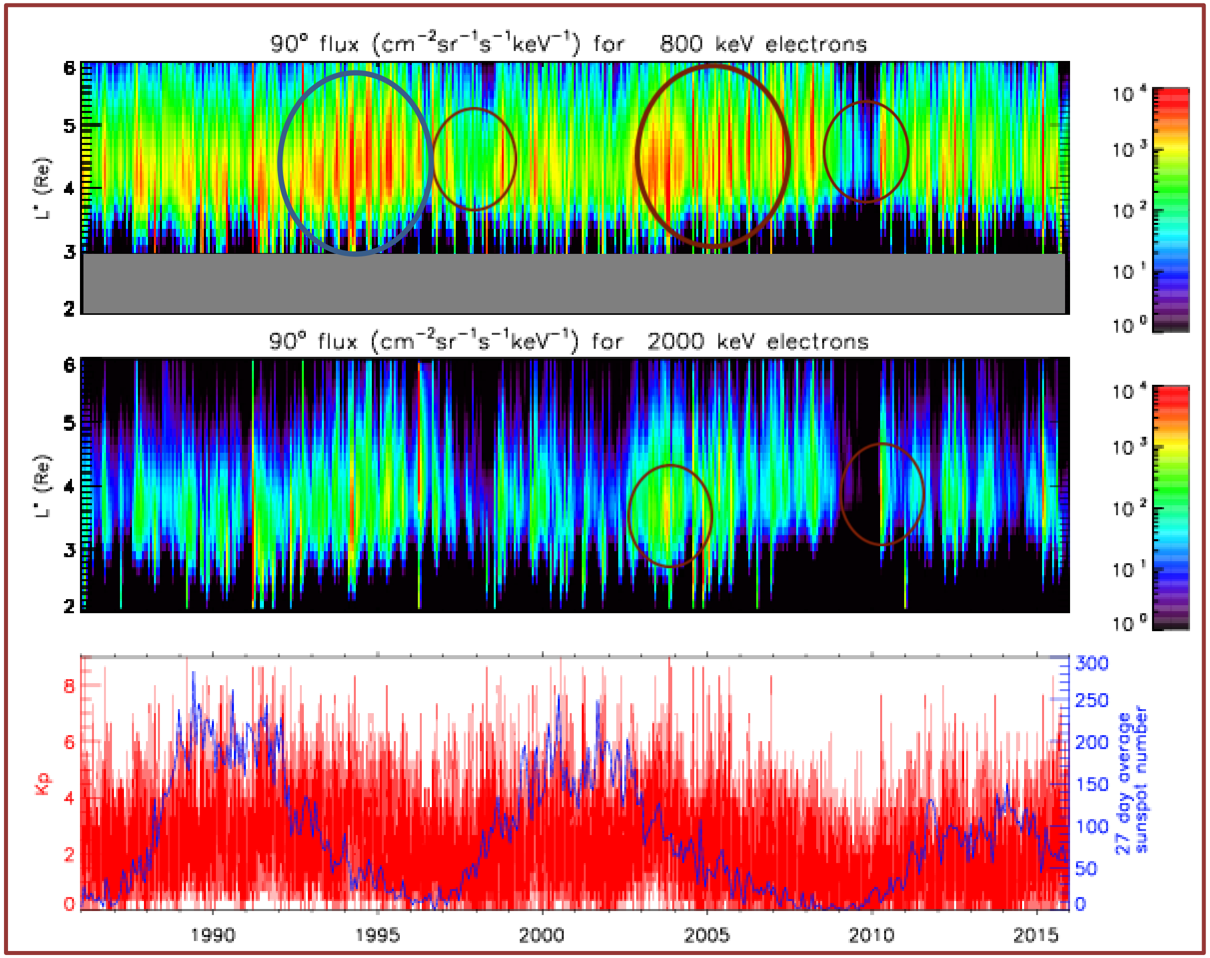
Most intense
in declining phase
1993-1994, 2003-2005

Quiet start to new cycle

1998, 2009

2 MeV at L*=3.5

peak flux can be
several orders of
magnitude different
for extended periods



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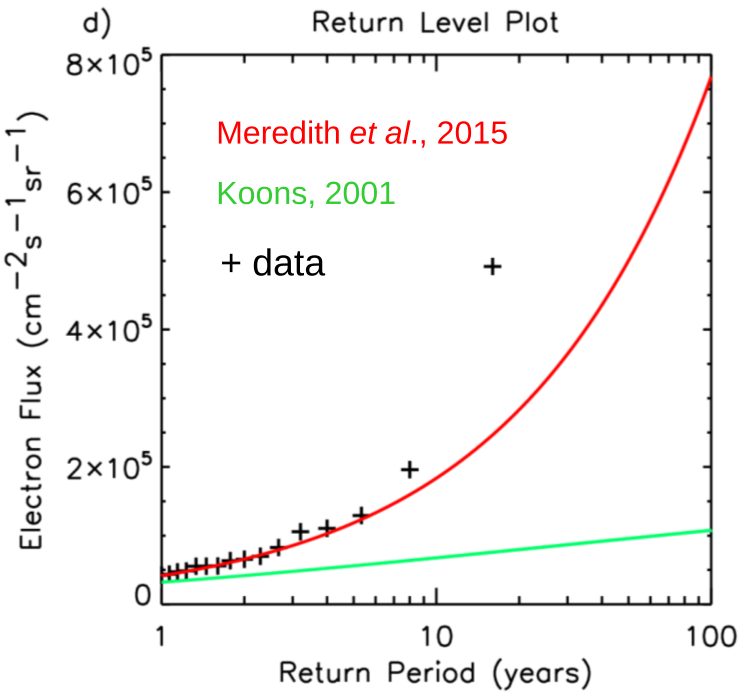
Extreme value analysis

- BAS conducted an extreme value analysis of 19.5 years of E > 2 MeV electron data from the GOES satellites at geosynchronous orbit. It was found
  - The 1 in 10 year flux at GOES West was 1.84×10^5 $cm^{-2}s^{-1}sr^{-1}$
  - The 1 in 100 year flux at GOES West was 7.68×10^5 $cm^{-2}s^{-1}sr^{-1}$
  - The 1 in 10 year and 1 in 100 year fluxes at GOES West were factors of 2.7 and 7 times those estimated by Koons [2001]



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Importance of keV electrons in the inner magnetosphere

- The distribution of low energy electrons population (10 to few hundreds of keV) constitutes the **seed population** further accelerated to MeV energies, critically important for **radiation belt** dynamics

- keV electrons are responsible for **surface charging** can cause significant damage and spacecraft anomalies

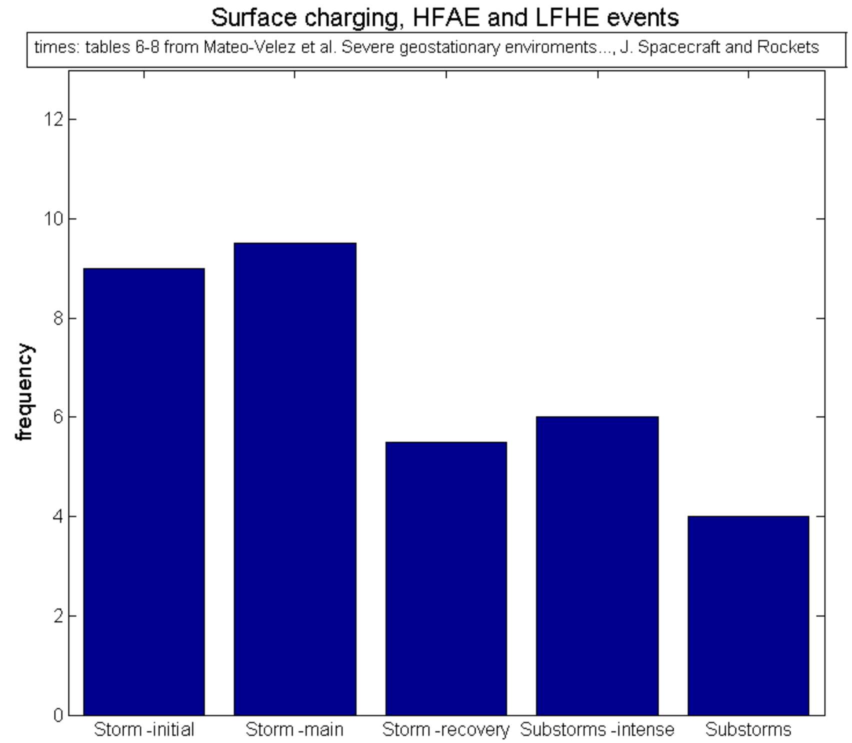
- **Louis Lanzerotti: Space weather is mor than storms**

It is **NOT necessary to have even a moderate storm for significant surface charging** event to happen

- The electron flux at the keV energies varies significantly with geomagnetic activity variations on time scales of minutes!

No averaging over an hour/day/orbit!

Surface charging events vs. geomagnetic conditions



Matéo Vélez et al., Severe geostationary environments: from flight data to numerical estimation of spacecraft surface charging, *Journal of Spacecraft and Rockets, 2016.*

SPACESTORM

It is not easy to model (nowcast) and forecast low energy electrons

• Following low energy electrons in large-scale **magnetic and electric fields:**
Correct models for these fields are extremely hard to develop

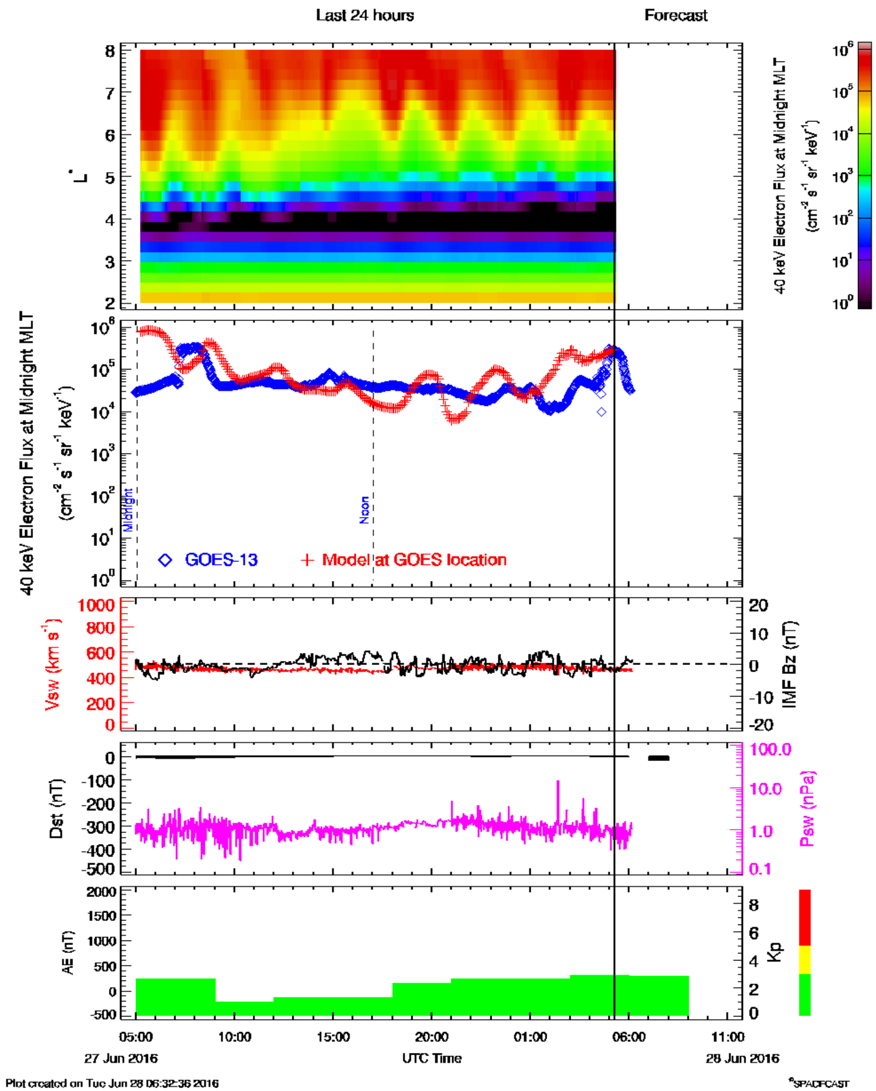
- Specification of a correct **initial conditions in the plasma sheet** is very nontrivial
- **Coefficients for radial diffusion** when electrons move from the plasma sheet (10 Re) to inner regions (<6 Re) are far from being exact.
- How to introduce low energy electrons' losses correctly? Electron lifetimes due to interactions with chorus and hiss, other waves, are they important?

- **MAIN FACTOR: SUBSTORMS**.

Substorms play a significant role in keV **electron transport and energy increase.**
How to include them properly?
- Like electromagnetic pulse? [*Li et al*., 1998*; Zaharia et al*., 2000*; Sarris et al*., 2002; *Ganushkina et al*., 2005, 2013; *Gabrielse et al*., 2012, 2014] What are the parameters? Most probably, not the amplitude. Location? MLT-width?
- Do we need different representations for different types of substorms (isolated substorms, storm-time substorms?
- Low energy electrons (at geostationary) are not organized by AE, KP-organization misses dynamics, IMF BZ and Vsw are main parameters.

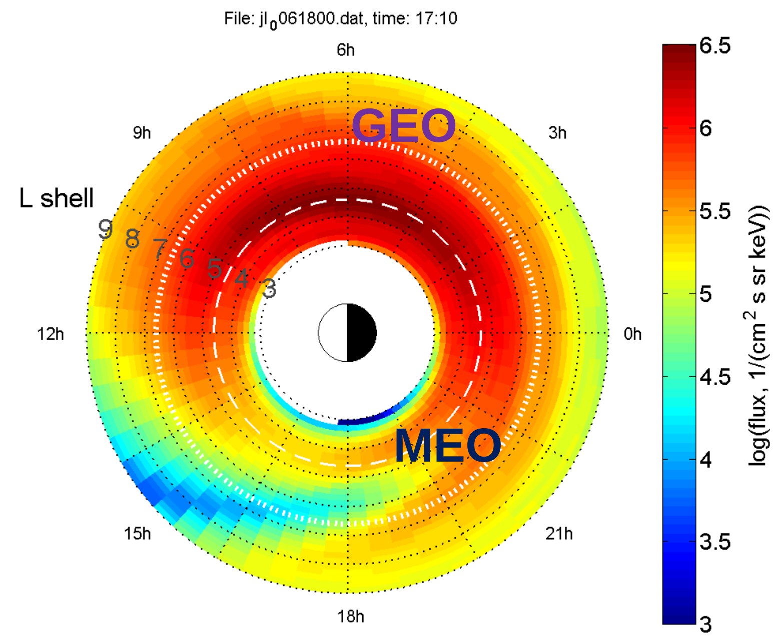
Present IMF and SW dependent models fail to represent the observed peaks associated with substorm activity

IMPTAM compared to GOES MAGED 40 keV e- fluxes



IMPTAM: traces **electrons (< 200 keV)** with arbitrary pitch angles (**drift approximation)** from the plasma sheet to the inner L-shells in time-dependent magnetic and electric fields

Taken into account: **radial diffusion and** electron losses as convection outflow and pitch angle diffusion by the **electron lifetimes**



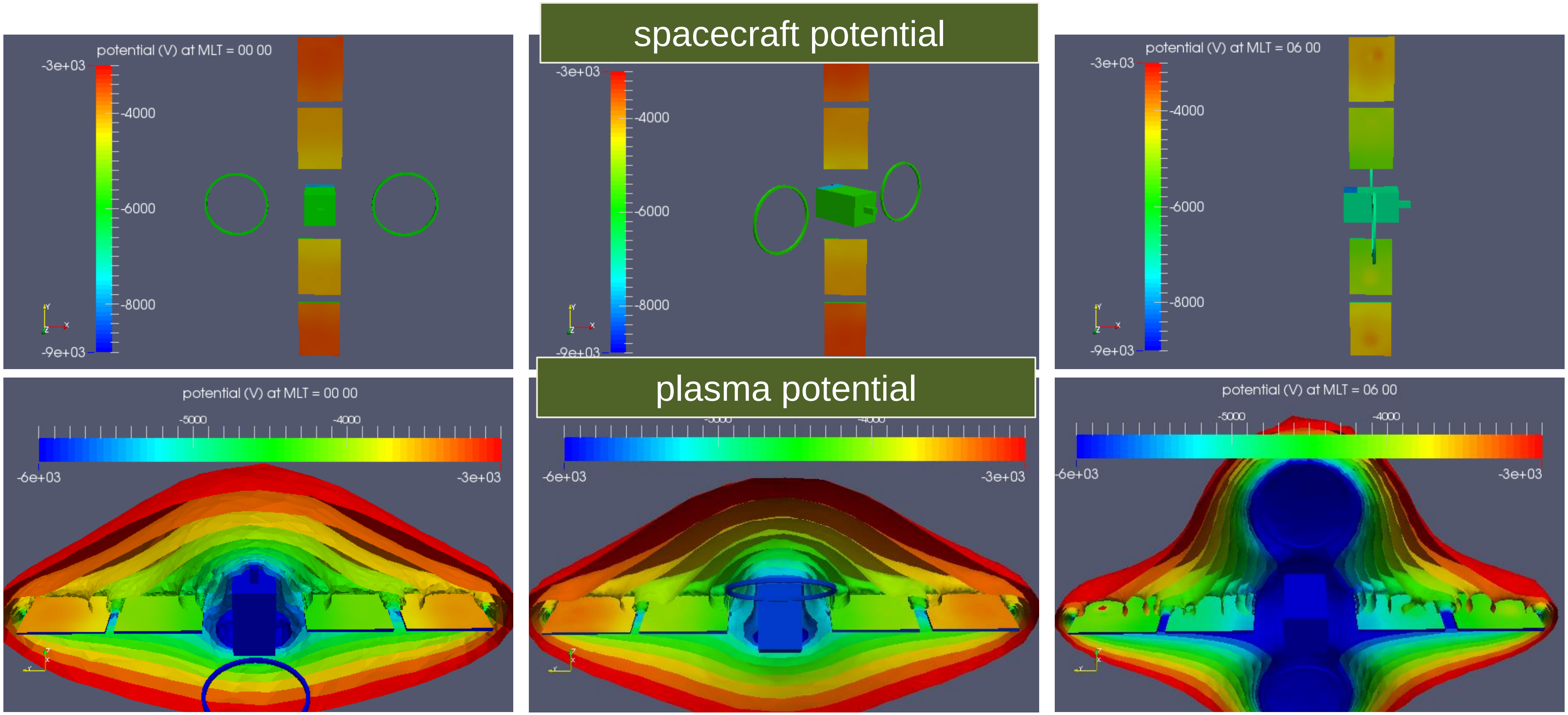
http://csem.engin.umich.edu/tools/imptam

imptam.fmi.fi

Ganushkina et al., JGR, 2013, 2014; Space Weather, 2015.

Surface charging risk assessment

00 MLT **03 MLT** **06 MLT**



Mateo-Velez et al 2016, 14th SCTC

With the same environment: Charging risk are more important at 06 MLT

The spacecraft attitude and of the area of conductive materials exposed to sunlight are very important

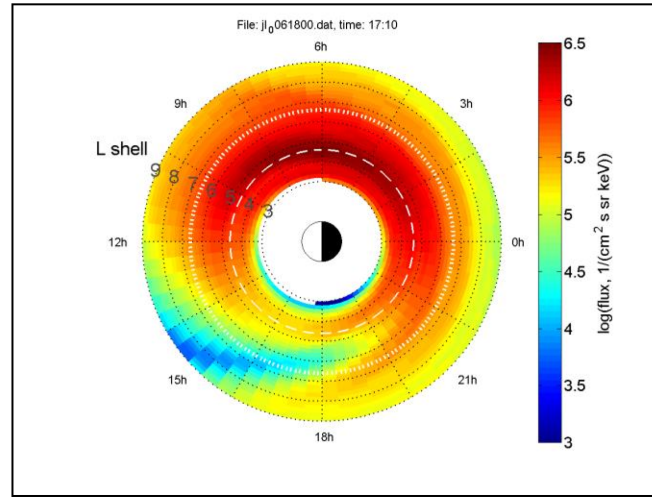
ONERA results

Charging at MEO

Very few data available

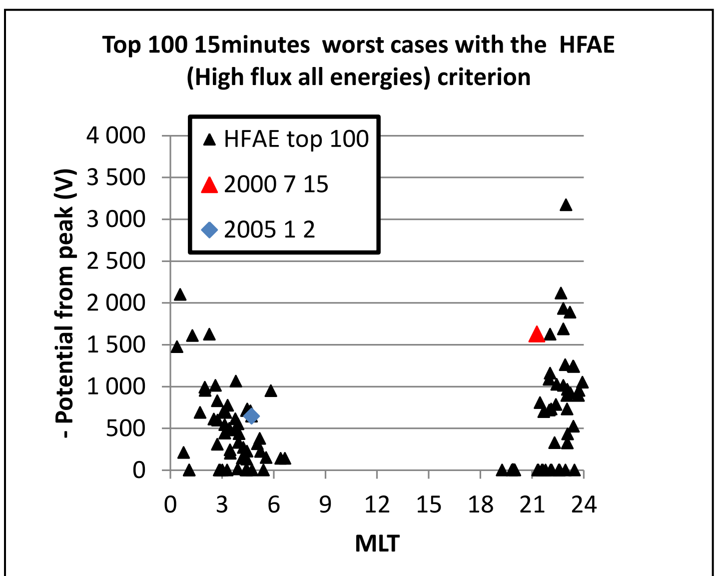
Method to obtain MEO worst case flux

1. Select dates of charging events at LANL (list provided by ONERA
2. Use the IMPTAM (FMI) to transport electrons from GEO (LANL) to MEO L = 4.6
3. Select time and position of worst case electron fluxes at MEO

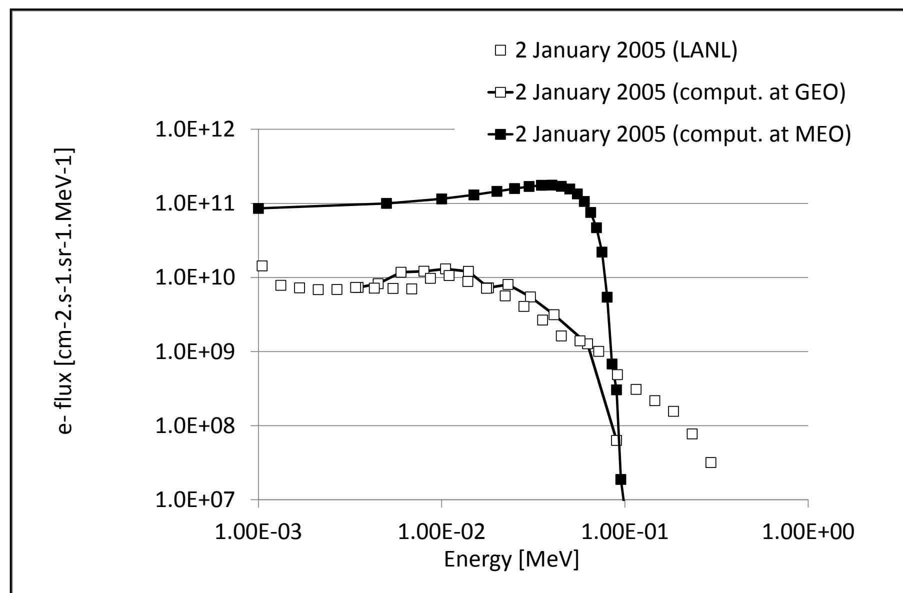


2.IMPTAM

Mateo-Velez et al 2016, 14th SCTC



1. GEO LANL (courtesy of CNES)



3. Specification at MEO

EU H2020 PROGRESS project overview
PRediction Of Geospace Radiation Environment and Solar wind parameterS

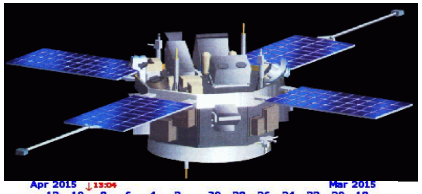
ssg.group.shef.ac.uk/progress/html

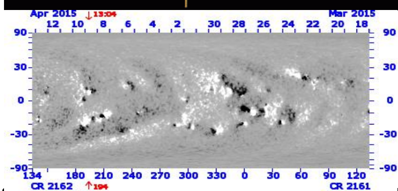
Participants:

(1) School of Mathematics and Statistics, Department of Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, UK
(2) Finnish Meteorological Institute, Helsinki, Finland
(3) University of Warwick, Coventry, UK
(4) University of Michigan, Ann Arbor, MI, USA
(5) Space Research Institute, Kiev, Ukraine
(6) Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, Orleans, France
(7) Swedish Institute of Space Physics, Lund, Sweden
(8) Helmholtz Centre Potsdam GFZ, Potsdam, Germany

The **overall aim** of the project PROGRESS is to exploit the available spacecraft and ground based data combined with state of art data assimilation methodologies in order to develop an accurate and reliable forecast of space weather hazards.

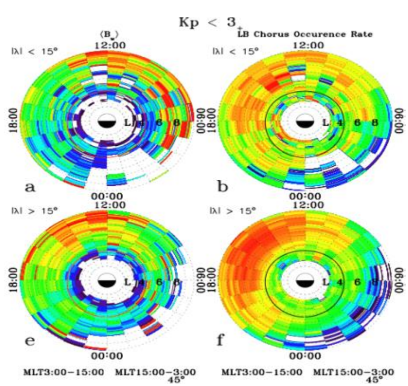
PROGRESS Overview





Solar wind propagation from Sun to L1 (AWSoM/SWIFT)

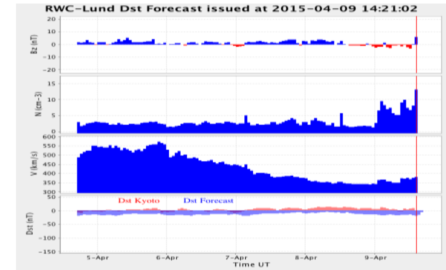
Development of new statistical models

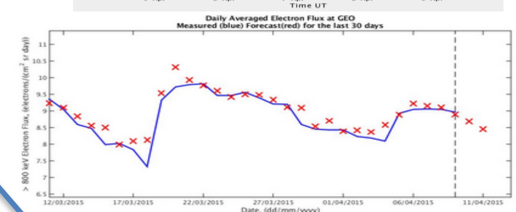


Low energy electron model

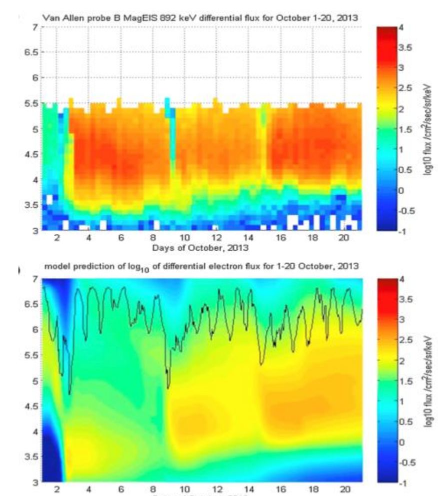
Forecast of the Evolution of Geomagnetic indices

Forecast of the high energy electron environment

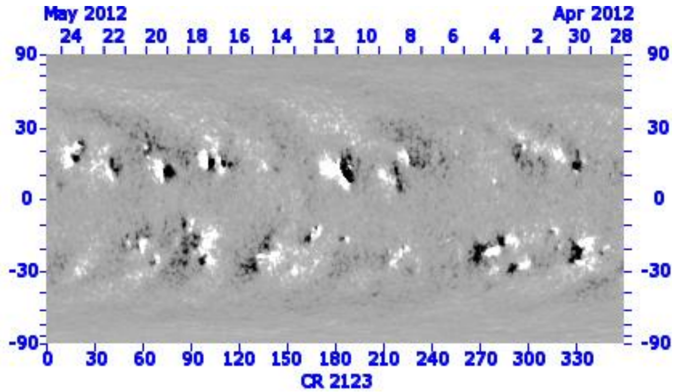




Fusion of forecast tools

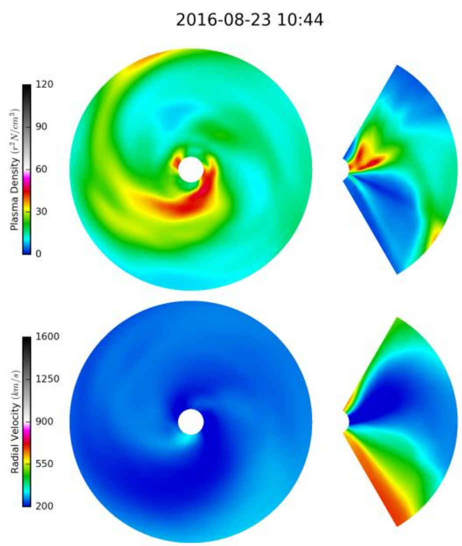


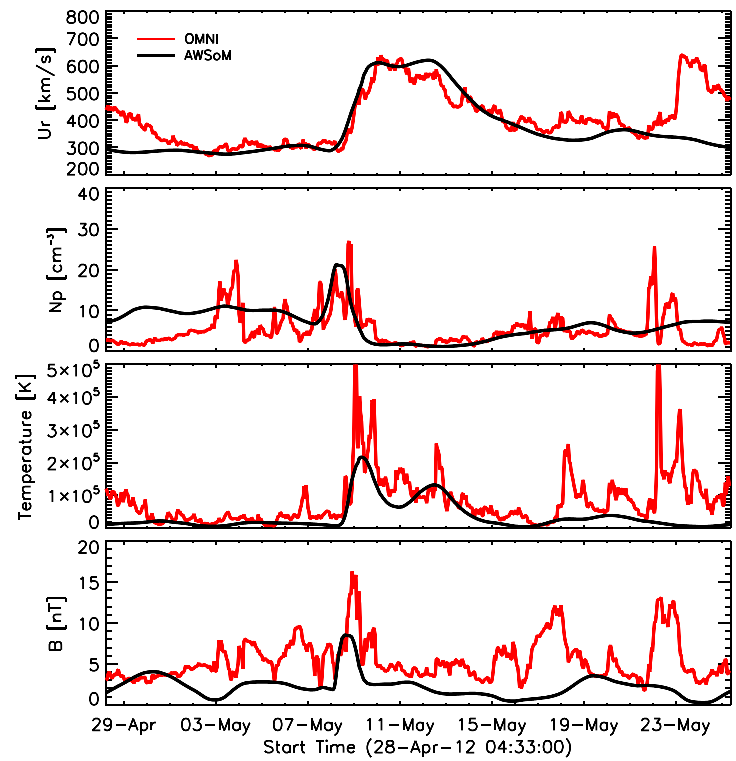
Prediction of L1 data from GONG



Collaboration between the **University of Michigan** and the **University of Warwick (UK)**
Start from GONG magnetogram data at the Sun
Use SWMF code AWSoM[1]
Predict conditions at ~25 Solar radii

Couple to spherical MHD code SWIFT
Propagate wind conditions out to L1 and Earth





The simulated solar wind properties along the Earth orbit and the OMNI data during CR2123

1. B van der Holst et al. ApJ 782, 81 (2014)

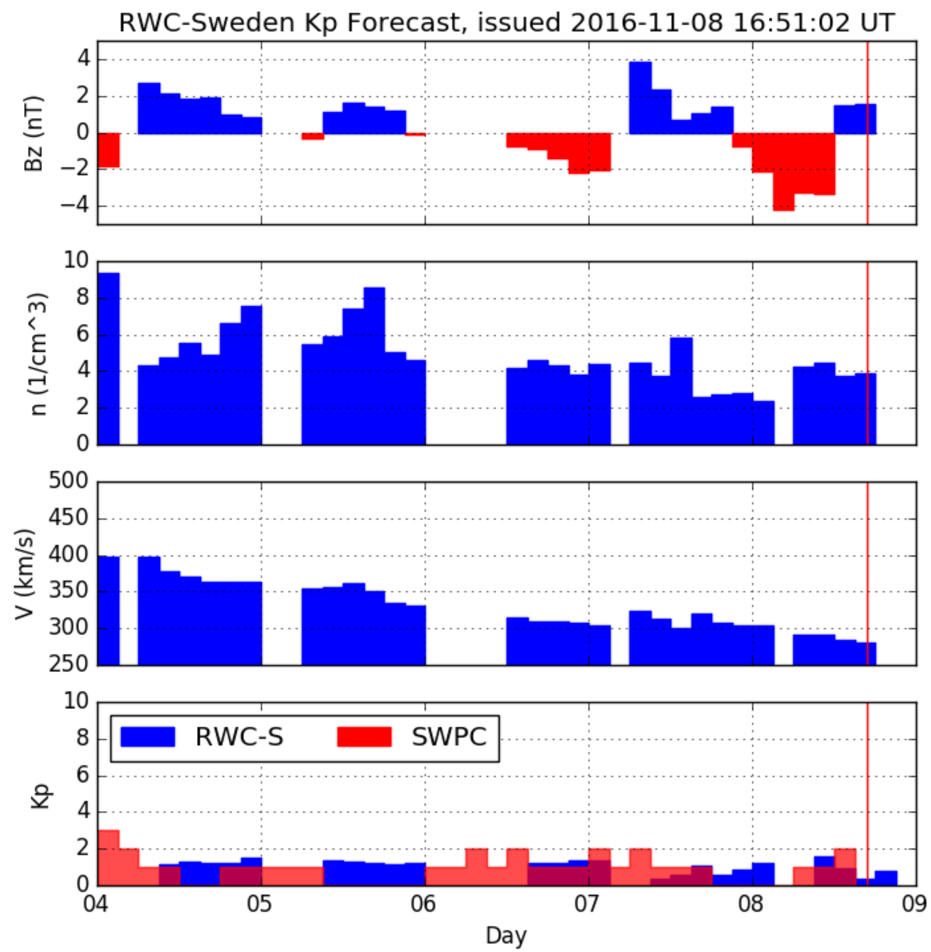
Forecast of geomagnetic indices

Geomagnetic activity expressed in terms of geomagnetic indices such as Dst, Kp, or AE

Indices are used as inputs to numerical models for radiation environment

Methodologies used

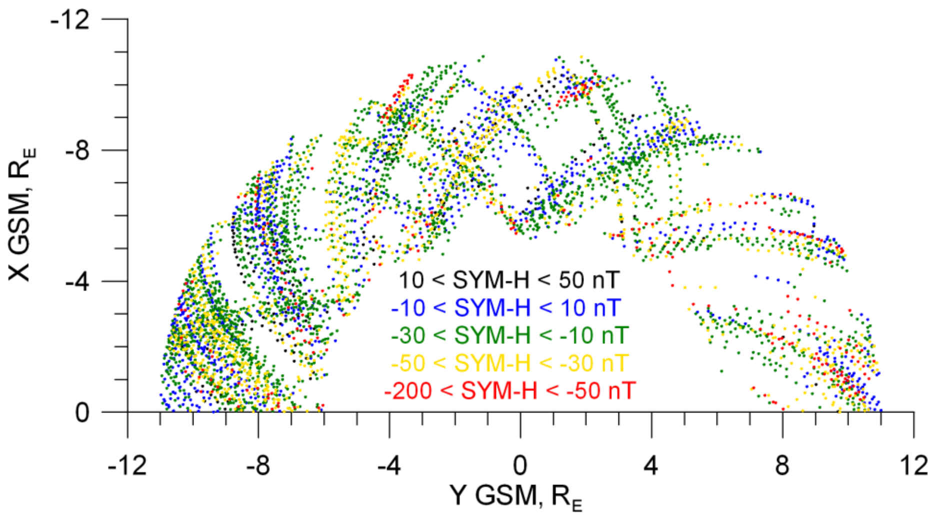
- Neural nets (IRF)
- NARMAX (U. Sheffield)
- NARMAX + Lyapunov exponents



Current status – a review of current online models performed as well as study of methods to assess quality

Swedish Institute of Space Physics, Lund, Sweden (http://www.lund.irf.se/rwc/)

New empirical plasma sheet model



Dubyagin et al., JGR, 2016

Analysed THEMIS data 6–11 Re
Data: THEMIS A, D, E probes;
ESA electrons: 30eV - 30 keV;
SST electrons ~25 keV - 300 keV

Density model: 2 input parameters
(1) Solar wind proton density
(2) IMF southward component
Temperature model: 3 input parameters
(1) Solar wind velocity
(2) IMF southward component
(3) IMF northward component

Both models show very good performance
Density: C.C.=0.82; RMS = 0.23 cm-3
Temperature: C.C.=0.75; RMS = 2.6 keV

Electron density model: 7 coefficients

$$N_e = 1.23 - 1.01\cdot r + 0.874\cdot r\phi^2 - 0.82\cdot\phi^2$$

positive → $+0.392\cdot N_{SW}$

positive → $\boxed{+(0.521-0.474\cdot r)}\cdot B_S$

Electron temperature model: 9 coefficients

$$T_e = [-0.0215 - 0.426\cdot\phi$$

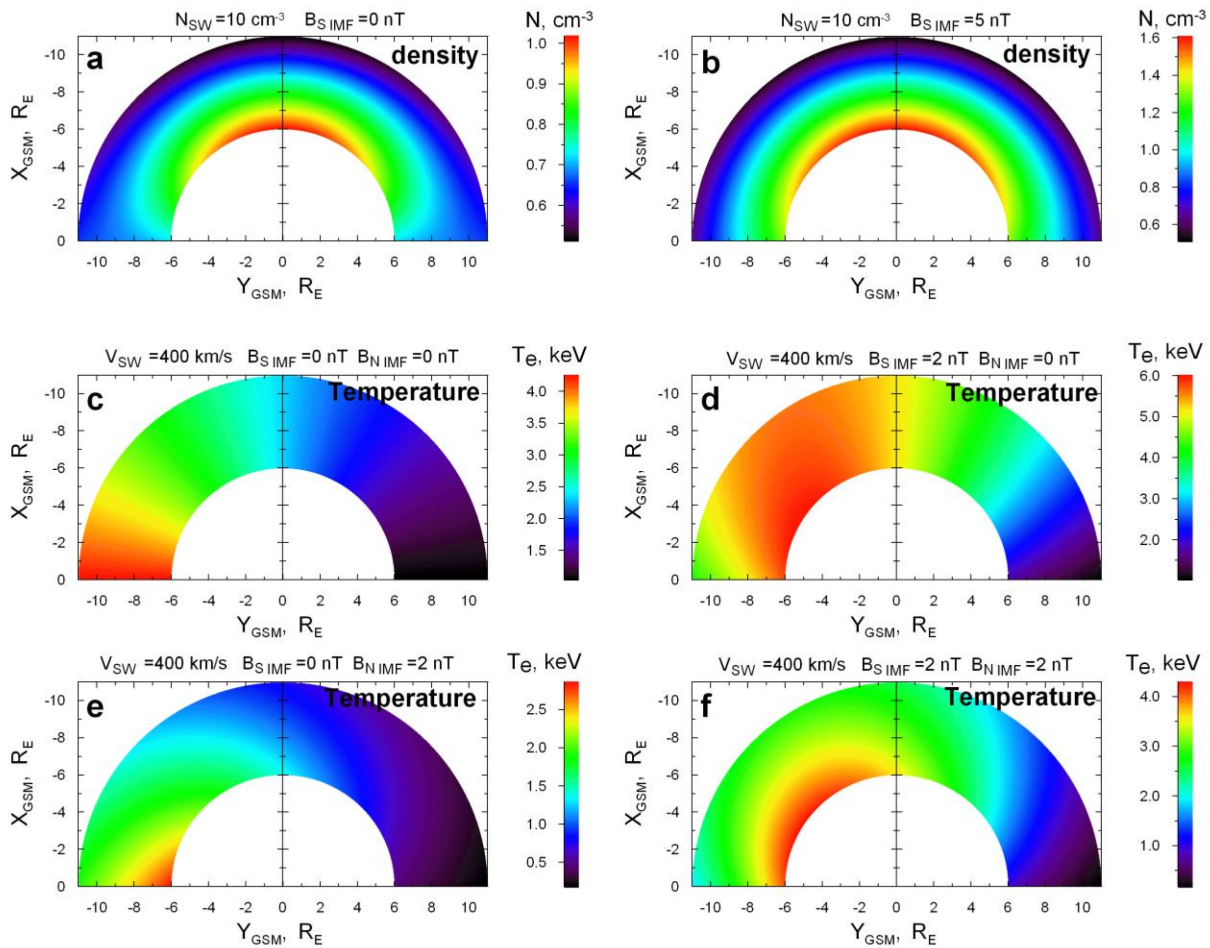
positive → $\boxed{+0.874}\cdot V_{SW}$

positive → $\boxed{+(0.587-0.538\cdot r\phi^2)}\cdot B_S^{0.32}$

negative → $\boxed{-0.489\cdot r}\cdot B_N^{0.36}]^{2.31}$

New empirical plasma sheet model

Dubyagin et al., JGR, 2016

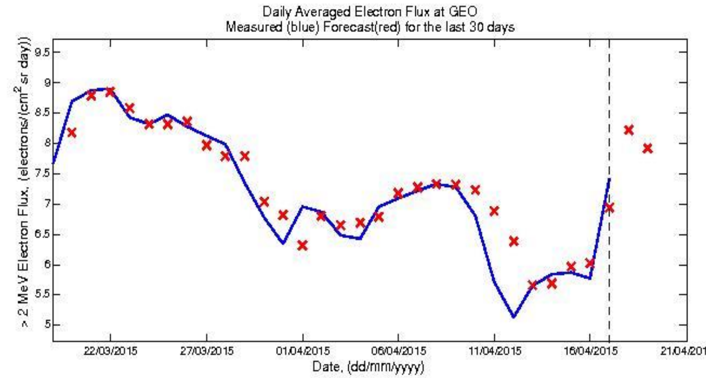


Note asymmetry in electron temperature

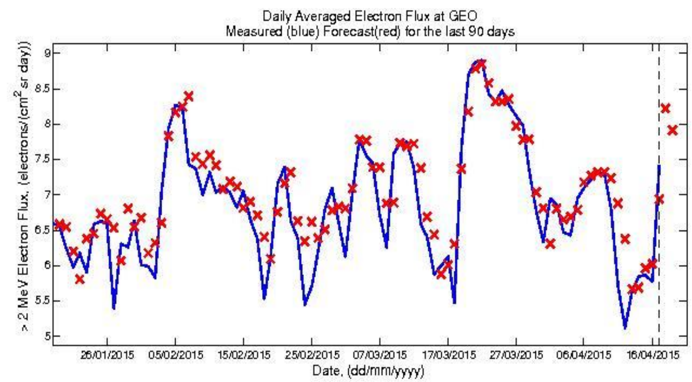
Model output can be used as a source for modelling inward transport of < 150 keV electrons

Online Forecasts – SNB^{3}GEO

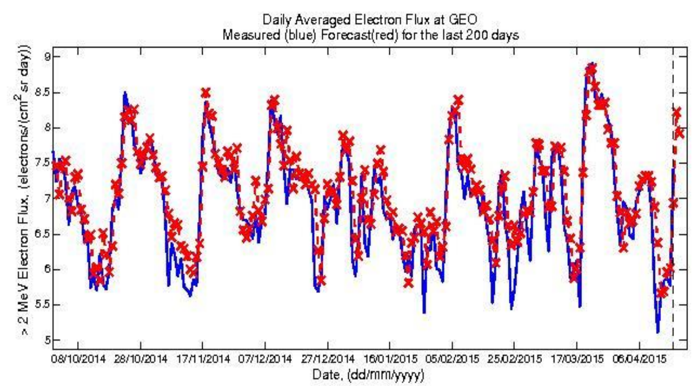
The one day ahead forecasts of the relativistic electron fluxes with energies greater than 2 MeV at GEO has been developed in Sheffield and is available in real time: http://ssg.group.shef.ac.uk/ssg2013/UOSSW/2MeV_EF.html



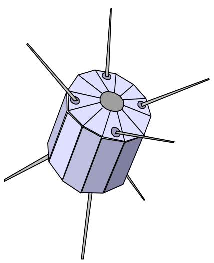
Past 90 days



Past 200 days



Input
ACE

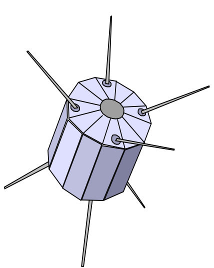


Velocity
Density
B_s fraction

<10 min

Forecast:
Daily averaged
Flux of
Electrons> 2MeV

Output
GOES



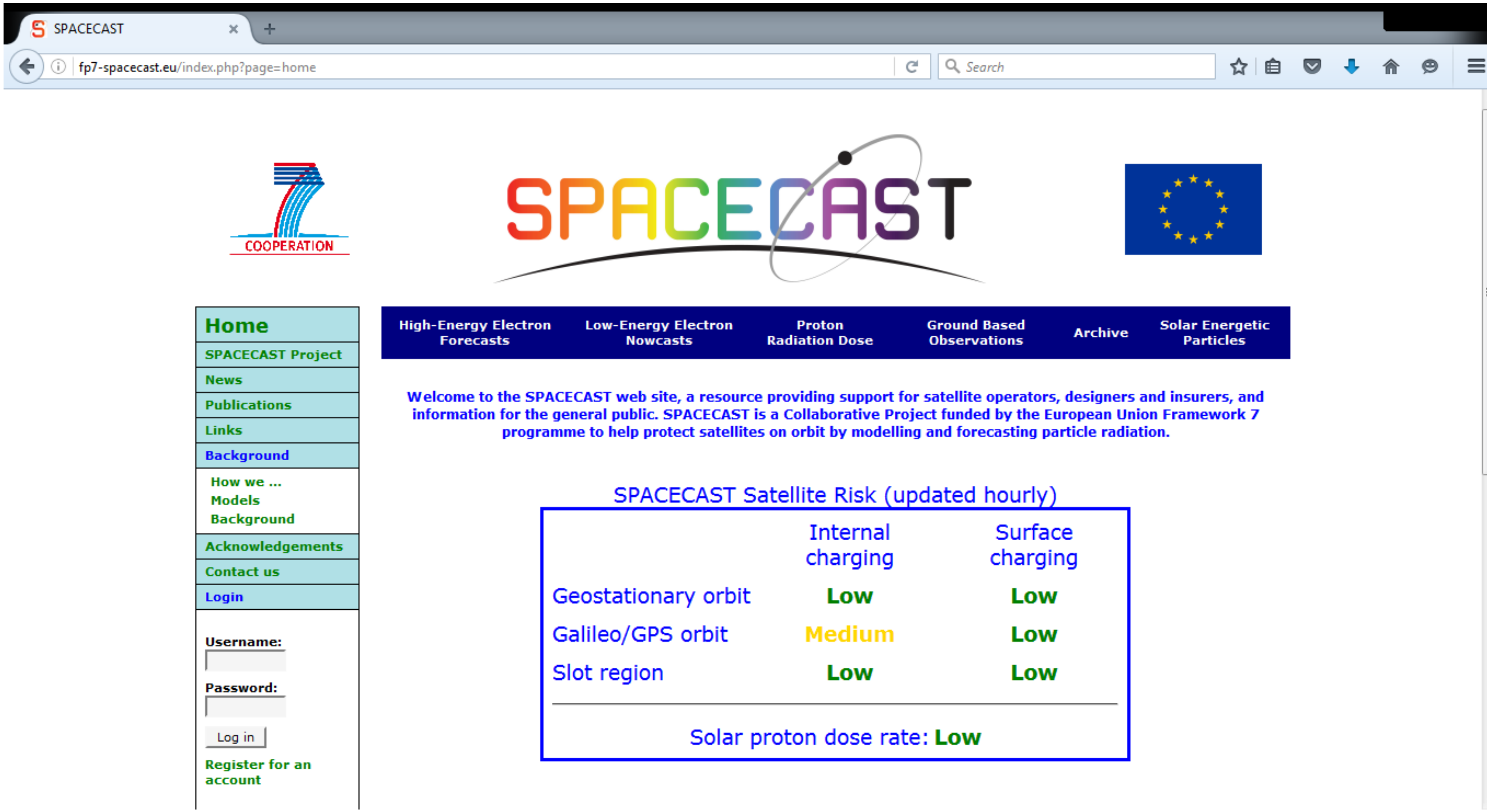
Comparison of REFM and SNB^{3}GEO forecasts

Balikhin et al., Space Weather, 2016

Model	Prediction Efficiency Flux	Correlation Flux	Prediction Efficiency Log Flux	Correlation Log Flux
REFM	-1.31	0.73	0.70	0.85
SNB^{3}GEO	0.63	0.82	0.77	0.89

PROGRESS

Experience from first EU-funded project: What end-users want is Traffic light



Determination of the 1 in N year event

- Our major objective is to determine the 1 in N year space weather event

- The flux that is exceeded on average once every N years can be expressed in terms of the fitted parameters σ and ξ as:

$$x_N = u + (\sigma/\xi)((N n_d n_c/n_{tot})^{\xi} - 1))$$

where n_d is the number of data points in a given year, n_c is the number of cluster maxima and n_{tot} is the total number of data points

- A plot of x_N against N is known as a return level plot