Characterisation of Near-Earth Magnetic Field Data for Space Weather Monitoring

Qingying Shu

University of Glasgow | School of Mathematics & Statistics

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    - Dr. Matteo Ceriotti (Space Engineering)
    - Prof. Lyndsay Fletcher (Physics & Astronomy)

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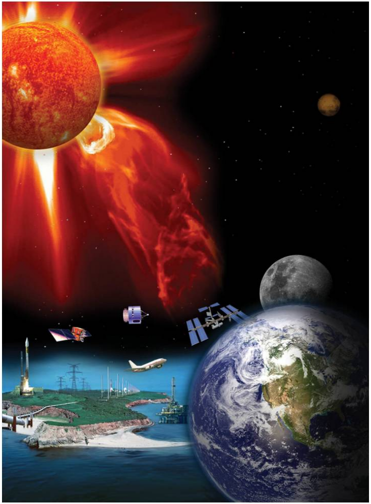
Outline

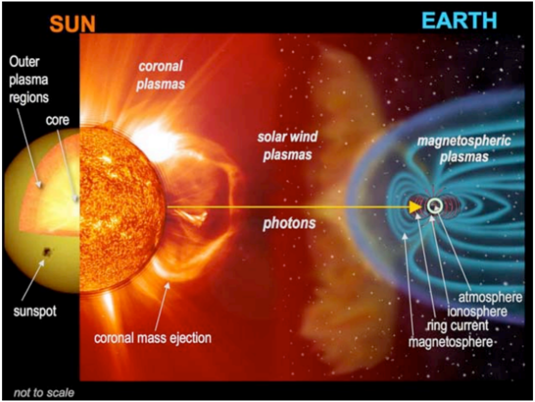
- Introduction
  - space weather
  - solar wind, magnetosphere, plasma interactions
- Motivation
  - geomagnetic storms
  - risk and priorities
- Goals
  - space storm prediction
  - constellations of small satellite
- Progress
  - exploratory analysis
  - characterization of magnetic field data
- Some Results
- Future Plans



NASA Space Weather Enterprise Forum

What is space weather?

- electromagnetic disturbances in the near-Earth environment
- caused by solar activity (flares, ejections, solar wind)
- associated with plasma interactions inside the magnetosphere



Space Weather: The Physics Behind a Slogan (2005), edited by Klaus Scherer

Why monitoring space weather?

- Severe space weather: geomagnetic storms
- Space weather is recognised as a significant and growing risk to infrastructure resilience (e.g. electric power grid, satellite communications, GPS, satellites and spacecraft).
- "Assessed risk of space-weather disruption in the next 5 years is:
  - Higher impact than a volcanic eruption
  - Same likelihood as weather extremes (heavy snow, heatwaves)"

  UK's National Risk Register, 2012

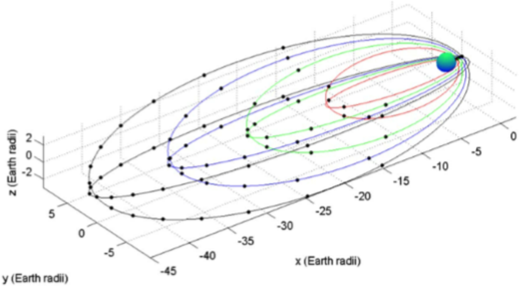
Space weather monitoring and early storm detection can be used to mitigate risks in sensitive technological systems.

Space weather monitoring

What are the best strategies for space weather monitoring with a network of small satellites?

Our goals:

- To develop new statistical methods which recognise the change in spatio-temporal sampling around an orbit
- To design a CubeSat constellation for sampling the magnetic field around the Earth



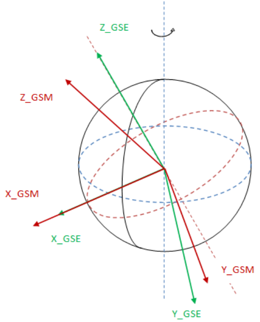
Progress - First Steps

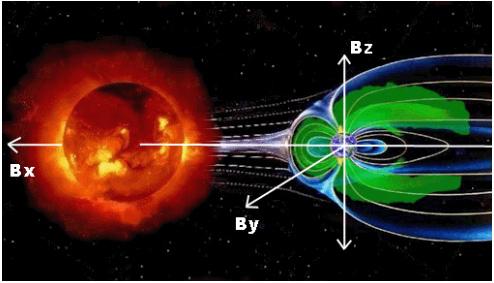
To understand the near-Earth space physics

- exploring the magnetic field vector $\mathbf{B} = (B_X, B_Y, B_Z)$ with
  - its corresponding position vector
  - satellite observation
  - model simulation
  - geomagnetic indices
- characterising the time-dependent variation in $\mathbf{B}$
  - case study - hourly sampled B_X in 2003
  - fitting statistical models to B_X with its potential covariates

Cluster mission

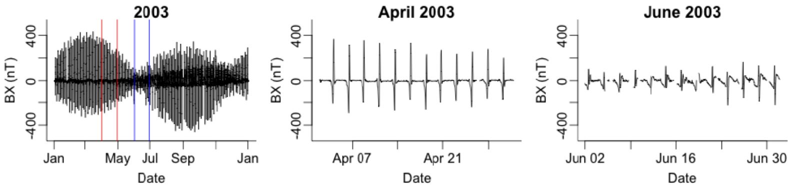
- use the data from Cluster mission as a pilot study.
- satellite measurements (B_X, B_Y, B_Z)
- position vector (X, Y, Z)
- coordinates transformation





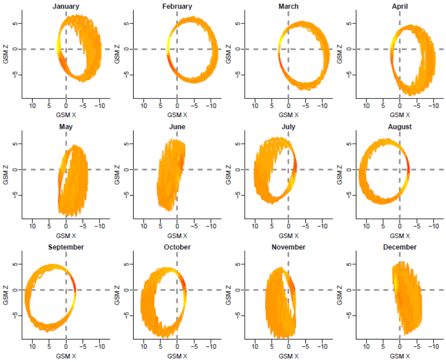
http://poleshift.ning.com

Cluster mission - temporal analysis



Credits: Peter F. Craigmile, The Joint Statistical Meetings 2014

Cluster measurements – seasonal orbits in B_X (nT) – 2003



Model simulation

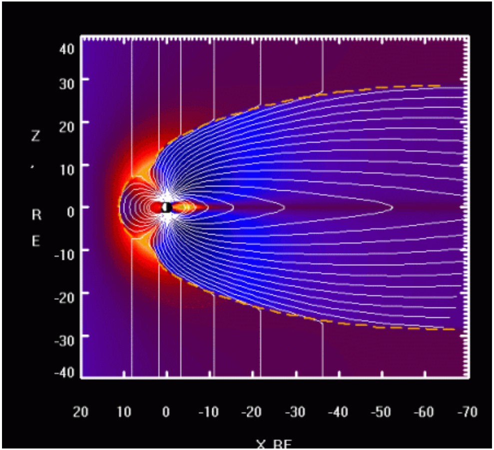
- The simulated magnetic field vector can be decomposed into

$$\mathbf{B} = \mathbf{B_I} + \mathbf{B_E}.$$

- the internal part $\mathbf{B_I}$ is generated from the Earth's dynamo
  - International Geomagnetic Reference Field (IGRF)
  - based on Gauss harmonic expansion for the scalar potential of the main geomagnetic field, static
- the external part $\mathbf{B_E}$ is associated with induced electric currents
  - Tsyganenko (T96) model
  - semi-empirical, best-fit representations, inputs of solar wind ram pressure, IMF, Dst index are needed
- can obtain IGRF and T96 values that coincide with the cluster measurements

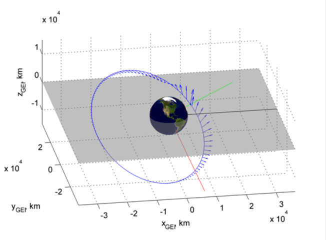
Model simulation - T96

The T96 model tells about the "average" conditions of the magnetic field at any location.



http://geo.phys.spbu.ru/ tsyganenko/modeling.html

Orbit & magnetic vector (Tsyganenko model)



Sensors Systems Update Meeting 2012

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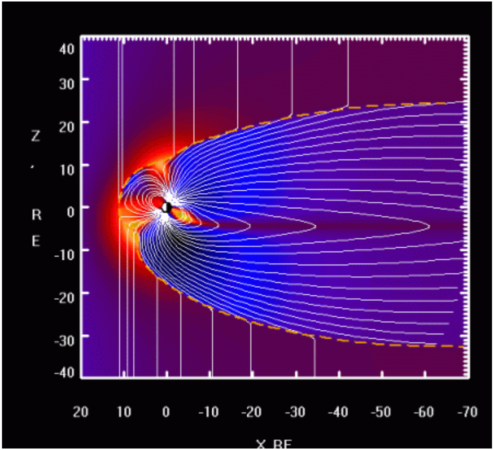

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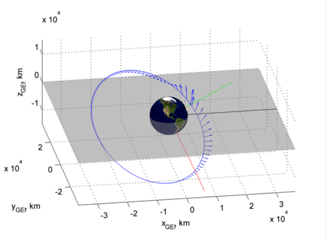

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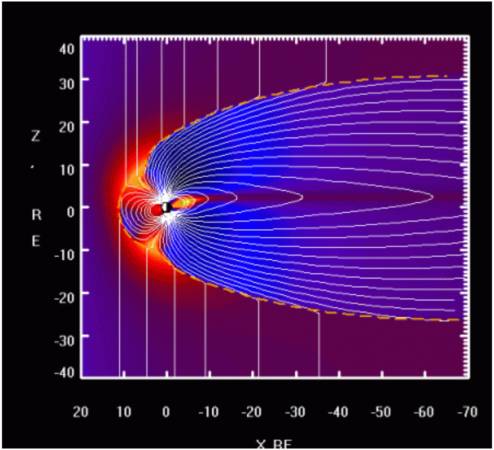

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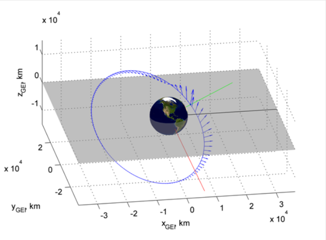

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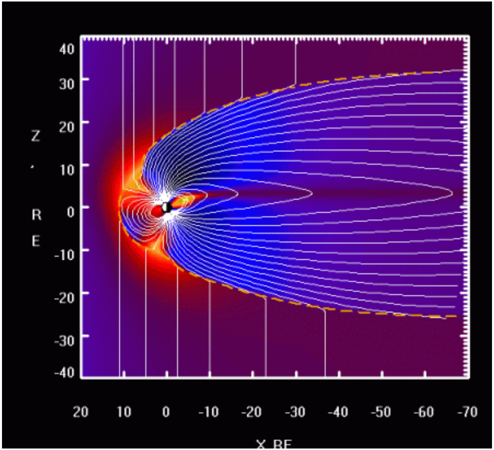

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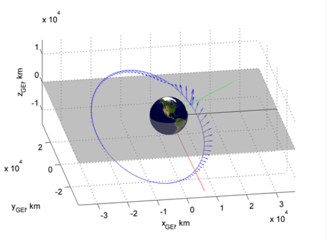

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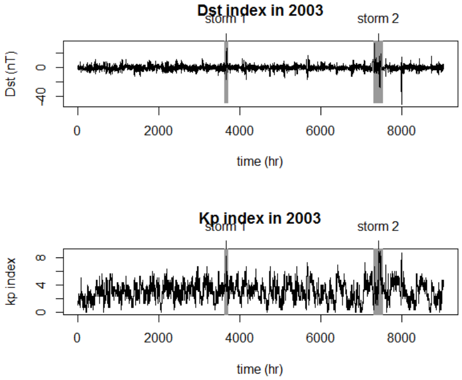
Geomagnetic indices

- Dst and Kp indices are indicators of geomagnetic activity
- two pre-defined storm periods



- Dst and Kp indices give partial information about storm conditions

Exploratory analysis - Statistical issues

Question of interest

How does the actual satellite data deviate from the model simulation, systematically or especially in storm conditions?

- Regression modelling
  - to understand the relationship between the satellite observations and the global model;
  - help achieve our goal of designing a network and identifying storms.
- Important covariates
  - $IGRF_X$ and $T96_X$
  - X, Y, Z position or orbital effect
  - proxy magnetic condition: Dst and Kp indices
- Residual autocorrelations and non-constant variance

Exploratory analysis - Linear regression

- best fit representation

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{p-1} X_{p-1} + \delta$$

  - the response Y is B_X;
  - the predictors $X_1, \cdots, X_{p-1}$ are $X, Z, IGRF_X, T96_X, Dst, Kp$;
  - δ is a discrepancy term:

```
Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.277e+00  3.371e-01   9.722  < 2e-16 ***
x            1.847e-05  2.257e-06   8.184 3.15e-16 ***
z            9.660e-05  4.424e-06  21.834  < 2e-16 ***
IGRFx        9.963e-01  2.116e-03 470.857  < 2e-16 ***
T96x         8.199e-01  8.031e-03 102.101  < 2e-16 ***
Dst          2.288e-01  3.943e-02   5.803 6.77e-09 ***
Kp          -8.431e-01  1.003e-01  -8.402  < 2e-16 ***
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1
```

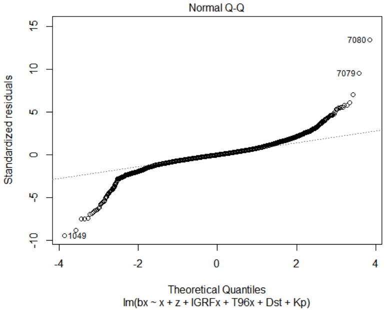
-

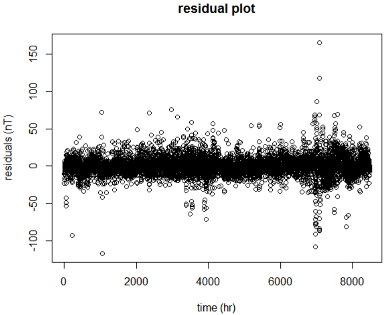
Exploratory analysis - Linear model diagnostics

- `Adjusted R-squared:  0.9695`

  from *R* output means that the fit explains 96.95% of the total variation in the data about the average.

- Diagnostics plots of our regression model suggest:

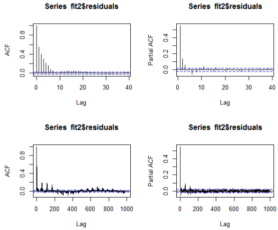




  - the discrepancy term δ does not follow a normal distribution;
  - non-variance is not accounted for by the model.

Exploratory analysis - Autoregressive model

- the discrepancy term forms a time series δ_t



- the AR(p) model is defined as

$$\delta_t = c + \sum_{i=1}^{p} \phi_i \delta_{t-i} + \epsilon_t$$

  Where $\phi_1, \cdots, \phi_p$ are the parameters, c is a constant, and ϵ_t is the error term.

- $p = 3$ is chosen, coefficients ϕ_1, ϕ_2, ϕ_3 and c are given in R output.

Some results

- Mode-based simulations, IGRFx and T96x, capture the main features in B_X;
- Geomagnetic indices, Dst and Kp, give partial information about the variation in B_X;
- Orbital effects can be modelled by the X and Z components in position vector;
- Time-varying effects exist in the discrepancy term.

The future

- Building multivariate spatio-temporal processes for magnetic field measurements (B_X, B_Y, B_Z)
  - to investigate ϵ_t for non-constant variance;
  - to consider interaction terms in linear model fitting
  - to perform analysis in terms of storm and non-storm behaviours.
- Identifying the signatures of space storm onsets;
- Designing satellite networks to detect and predict storm events.