



Multivariate autoregressive (AR) prediction of MeV electron flux variation in Geostationary and Medium Earth orbits

Kaori Sakaguchi and Tsutomu Nagatsuma*

National Institute of Information and Communications Technology
(NICT), Japan



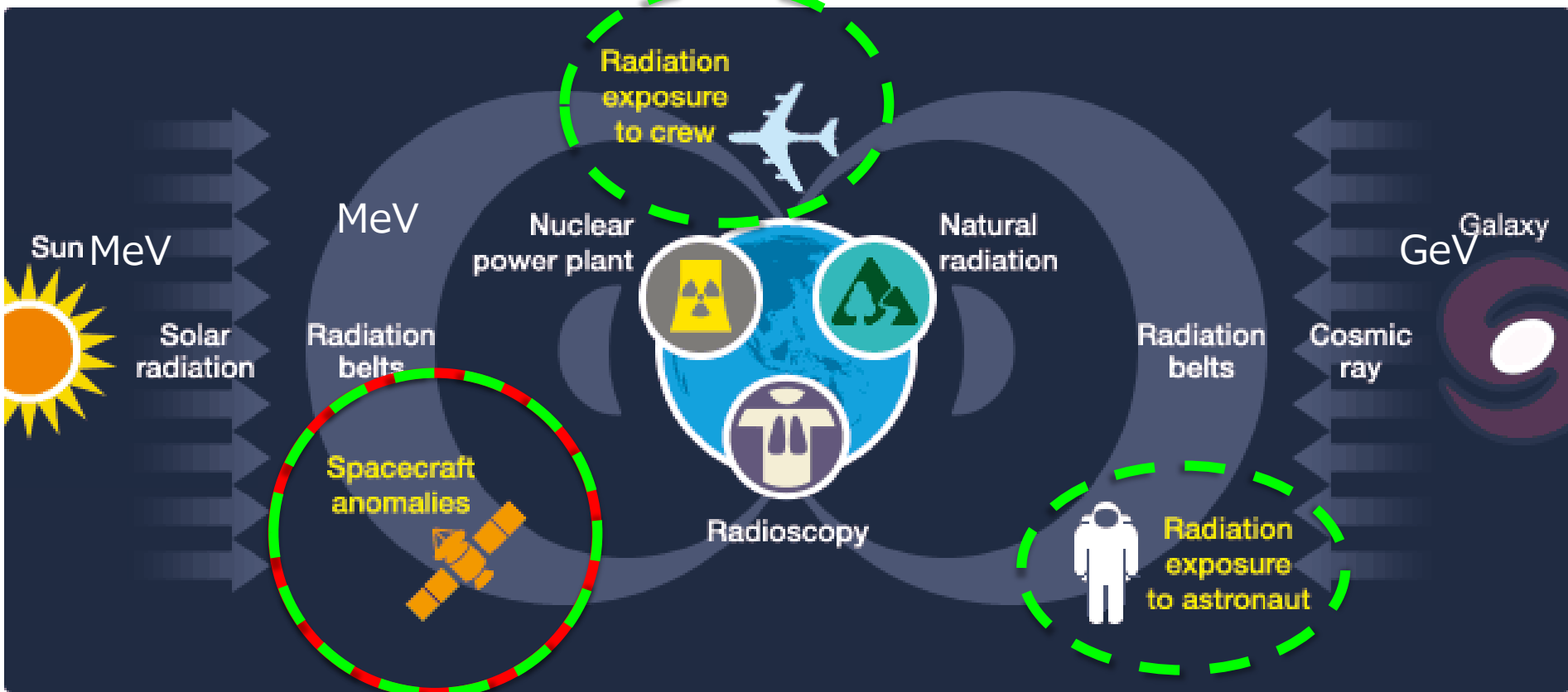


Outline

- Introduction
 - Satellite Anomaly
 - New particle observation by Himawari/SEDA
- Method and results of our model
 - Himawari/SEDA
 - Van Allen Probes
- Summary



High-energy particles in Geospace and risk for space utilities



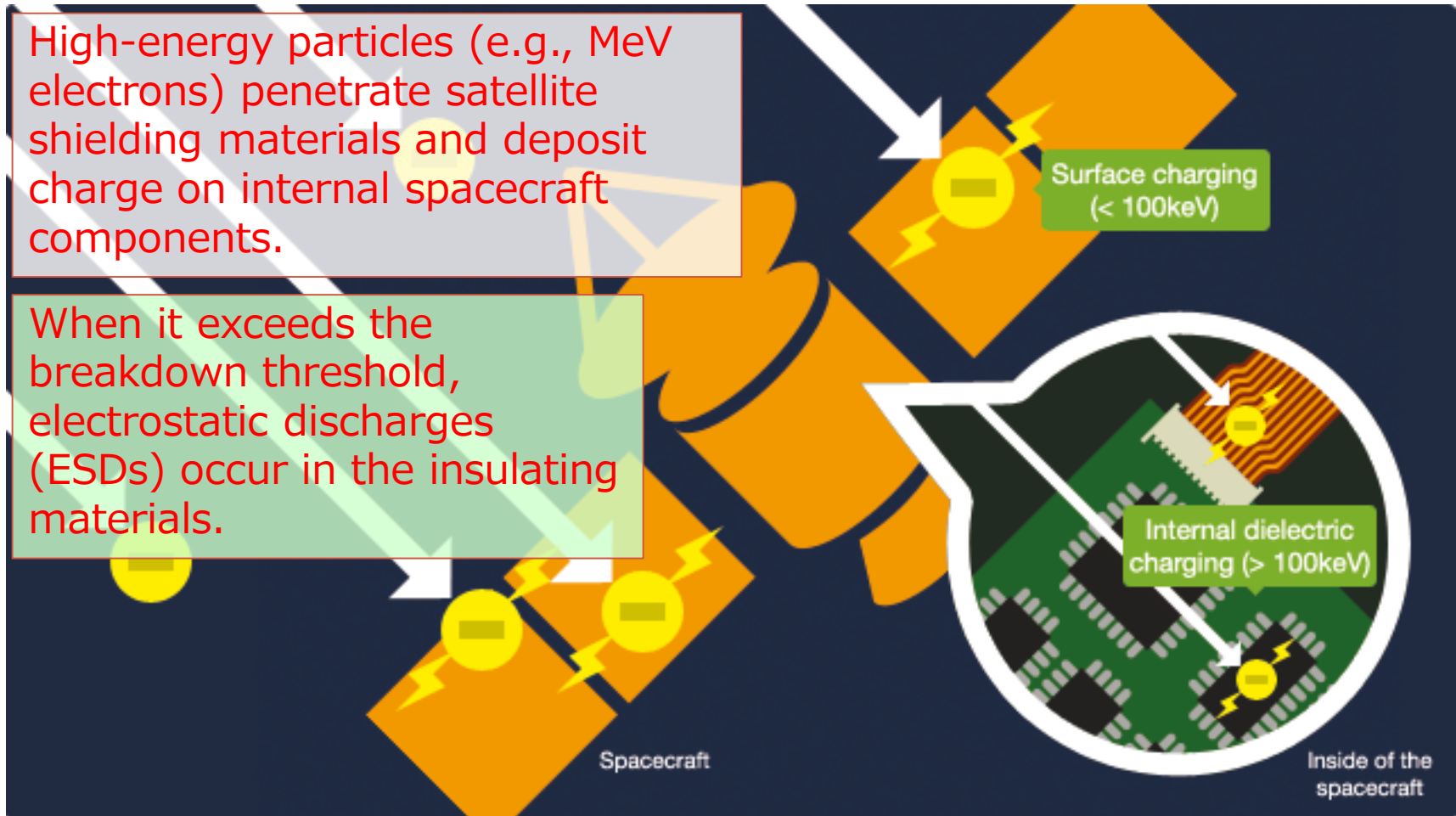
↑
**Topic of this presentation
(radiation belt electrons)**



Spacecraft anomaly by deep dielectric charging

High-energy particles (e.g., MeV electrons) penetrate satellite shielding materials and deposit charge on internal spacecraft components.

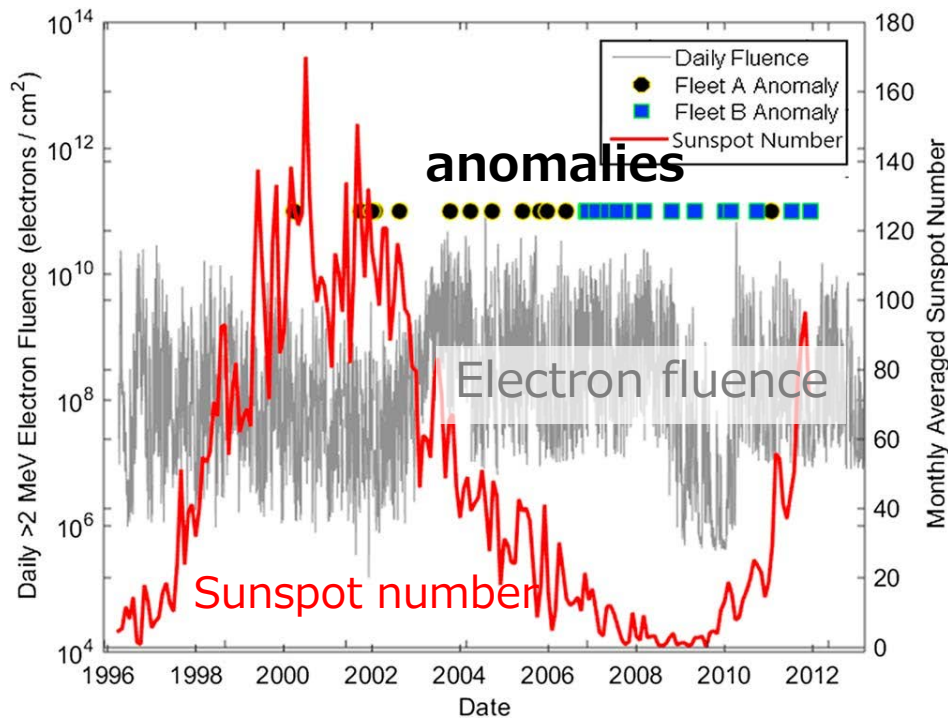
When it exceeds the breakdown threshold, electrostatic discharges (ESDs) occur in the insulating materials.





Examples of anomalies:

Communications satellites at GEO [Lohmeyer and Cahoy, 2013, 2015]



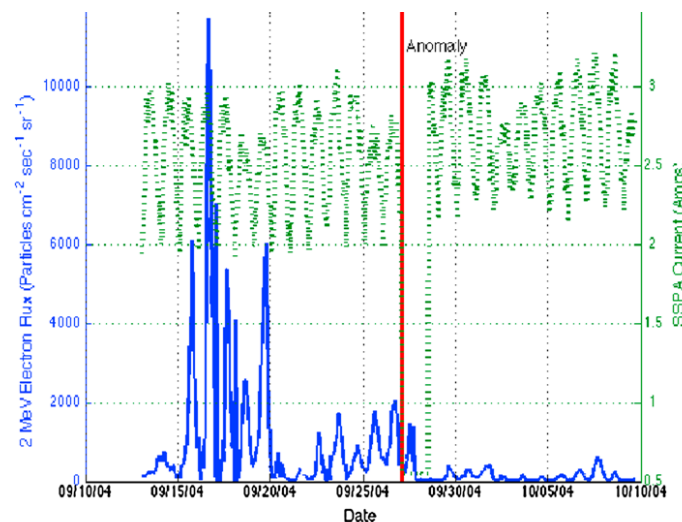
wn in red.

Lohmeyer and Cahoy, 2015

Inmarsat

power amplifier anomalies

- ✓ frequently occur in the declining phase of solar cycle.
- ✓ tend to occur electron fluence accumulated over 14 and 21 days.





Energetic particle monitoring over Japan by the meteorological satellite HIMAWARI-8

- **Instrument: SEDA (Space Environment Data Acquisition monitor)**
- **Purposes: house-keeping and failure analysis**
- **Launch: 2014/10/07, Himawari-9 Launch; 2016 (plan)**
- **Longitude: ~ 140 deg.**
- **SEDA data is available from Nov. 03, 2014**
- **Near-real time SEDA data is archived at NICT.**



electron sensors

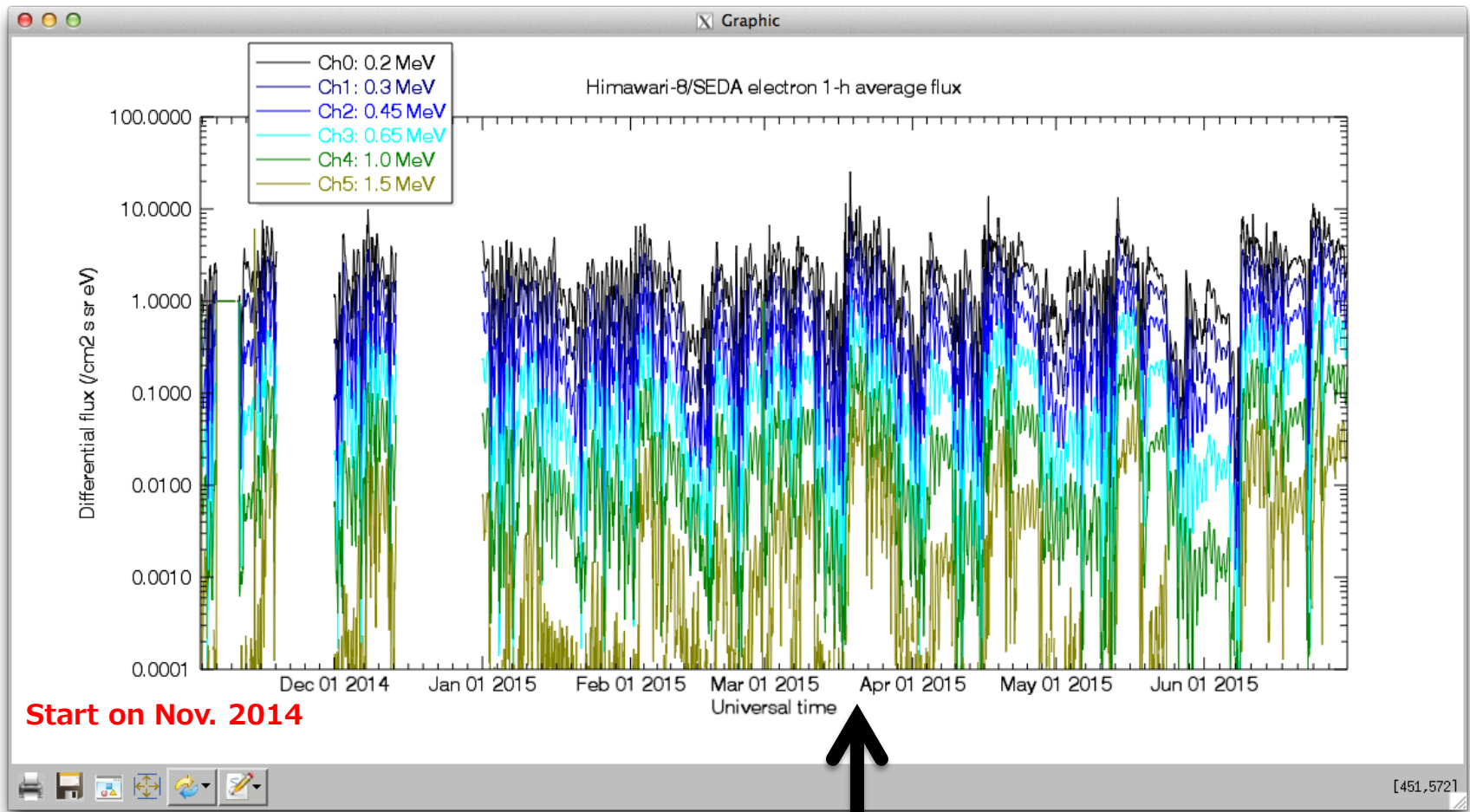
proton sensors



Electrons: 8 ch. (8 series plate)
Protons: 8 ch. (8 sensors)
Electrons: 0.2 MeV \sim 5 MeV
Protons: 15 MeV \sim 100 MeV
Electron sensor: $\pm 78.3^\circ$
Proton sensor: $\pm 39.35^\circ$
Time resolution: 10 s



SEDA observation data electron flux (0.2 – 1.5 MeV)



3-Dimensional Geospace Monitoring Network

Himawari-8/SEDA data as a source of global space environment monitoring around GEO,

Kodama(DRTS)
(JAXA)

Japanese GEO Satellites are operated in this area.

GOES 13
(NOAA)

Van Allen Probes
(NASA)

AC Mag.

HF radar

DC Mag.

ERG(JAXA)
(plan:2016)

Himawari-8 (JMA)
Himawari-9 (plan:2016)

GOES 15
(NOAA)



How to Predict?

✓ Numerical simulation?

✓ Empirical model?



Multivariate autoregressive (AR) model + Kalman filter

Autoregressive (AR) model can estimate future flux variations on the basis of its lagging correlation with changes in other parameters [Sakaguchi et al., 2013].

$$Y_t = \sum_{n=1}^m A_n Y_{t-n} + v_t,$$

$$Y = \begin{bmatrix} y_1 & \cdots & y_k \end{bmatrix}^{-1}$$

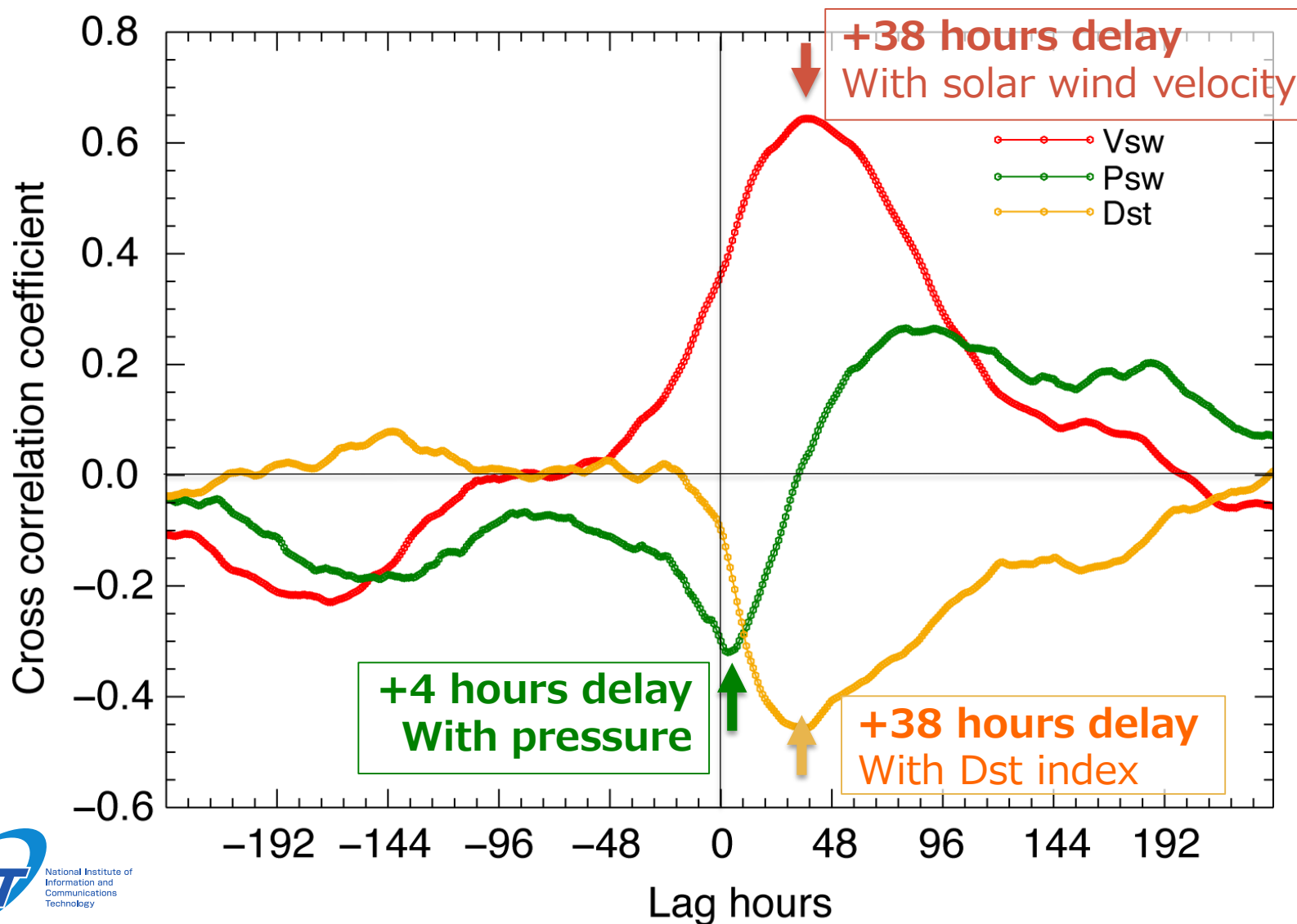
y_1 : predictor variate (flux)

y_k : explanatory variate (solar wind)

- ✓ Daily average electron flux variations correlate positively with corresponding averages of the **solar wind flow speed** near the Earth [e.g., Paulikas and Blake, 1979]
- ✓ Relativistic electron flux largely decreases, when the **solar wind dynamic pressure** increases. [e.g., Turner et al., 2012].
- ✓ The high-speed solar wind stream with **southward offset in the IMF B_z** enhances the electron flux more than that without offset. [Miyoshi and Kataoka, 2005]



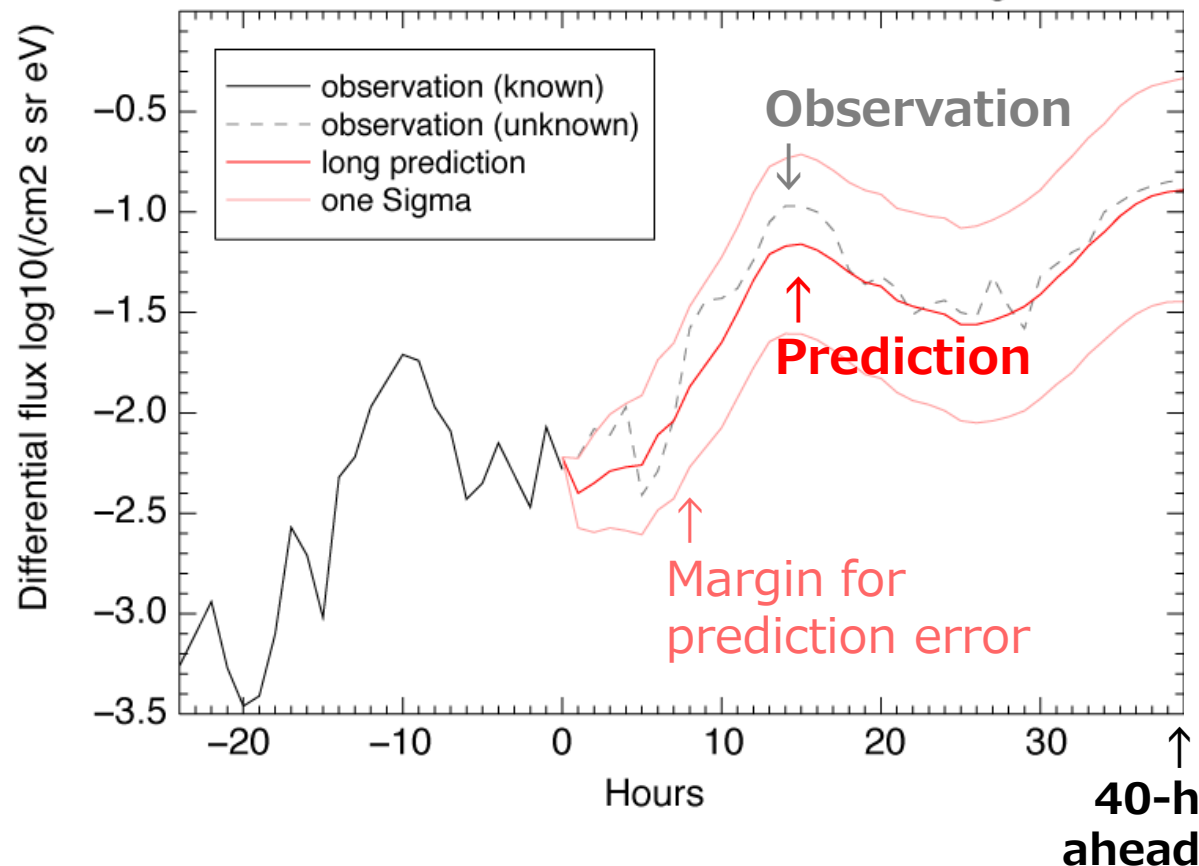
Cross-correlation functions between HIMAWARI SEDA electron flux and other parameters





Time series prediction result of GEO MeV flux by AR model + Kalman filter

Himawari-8/SEDA 1.0 MeV electrons 1-h average flux



$$Y_t = \sum_{n=1}^m A_n Y_{t-n} + v_t,$$

Regression order

— 28 hours

Inputs

— Solar wind velocity

— Solar wind pressure

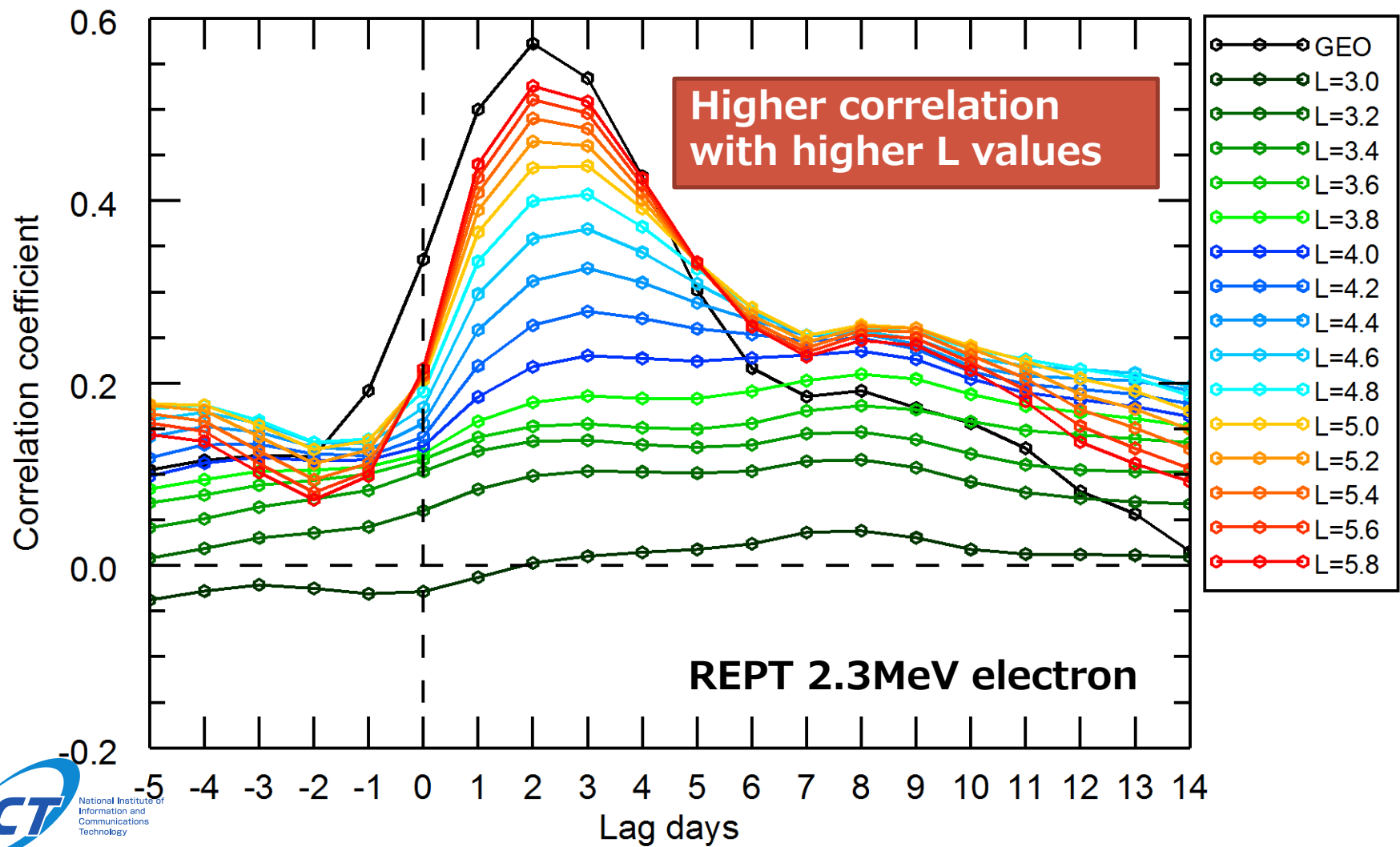
— Dst index

#Coefficient matrix A is estimated by the least square method



Cross correlation functions w/ Vsw for each L shell (by Van Allen Probes data)

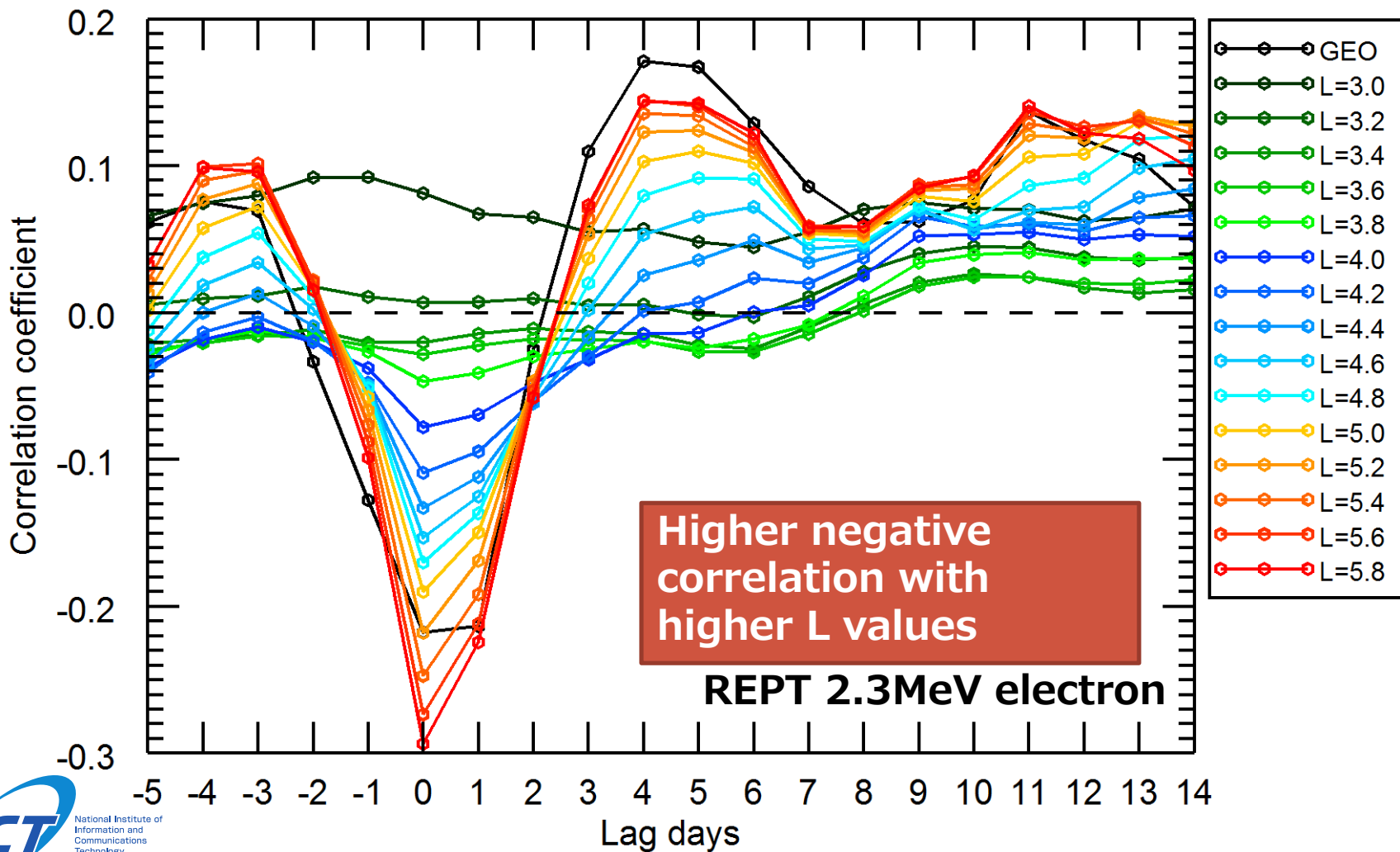
Cross correlation with solar wind speed





Cross correlation functions w/ Psw for each L shell (by Van Allen Probes data)

Cross correlation with solar wind pressure





Effective combinations of input parameters

L values	Regression	Input parameters
L=3.0	5 days	Dst index
L=3.2	5 days	Dst index
L=3.4	2 days	Dst index
L=3.6	2 days	Dst index
L=3.8	2 days	Dst index
L=4.0	2 days	Dst index
L=4.2	2 days	Dst index + GEO flux
L=4.4	2 days	Dst index + GEO flux
L=4.6	2 days	Dst index + GEO flux
L=4.8	2 days	Dst index + solar wind speed + GEO flux
L=5.0	2 days	Dst index + solar wind speed + GEO flux
L=5.2	2 days	Dst index + solar wind speed + GEO flux
L=5.4	8 days	Dst index + solar wind speed
L=5.6	2 days	Dst index + solar wind speed + solar wind pressure
L=5.8	2 days	Dst index + solar wind speed + solar wind pressure
GEO (6.6 RE)	3 days	Kp index + solar wind speed + solar wind pressure



Discussion about input parameter transition by L values

- The **Dst** index is the best overall single parameter for predicting at $3 \leq L \leq 6$, while for the **GEO** flux prediction, the **Kp** index is better than Dst.
- The **V_{sw}** parameter is effective for the models at $L \geq 4.8$ only. This might be related to the inner edge of particle acceleration by ULF waves, a role of inward radial diffusion to lower L shells, the average, location of the plasmopause and the role of local acceleration by electrons interacting with whistler mode chorus outside of the plasmasphere.
- The **P_{sw}** parameter is effective for the models at $L \geq 5.6$ only. The boundary seems to be related to MeV electron loss owing to magnetopause shadowing. (statistical threshold from September 2012 to December 2013).

L-time diagram prediction of the outer radiation belt



The model successfully predicts the timing and location of the flux maximum as much as 2 days in advance and that the electron flux decreases faster with time at higher L values, both model features consistent with the actually observed behavior.

Observation

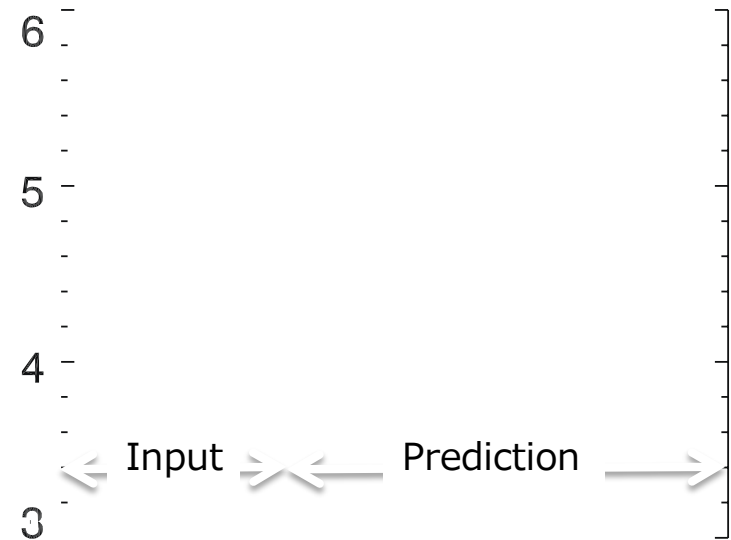
(VAP/REPT-A 2.3 MeV electrons)

days

Observed flux $\log_{10}(/cm^2 sr s MeV)$

Kalman Prediction

(over 10 days after day=0: 131)



days

Predicted flux $\log_{10}(/cm^2 sr s MeV)$





Summary

- We have developed prediction models of MeV electron flux in the outer radiation belt using energetic particle data from GOES, HIMAWARI, and Van Allen Probes. These models are based on multivariate AR analysis and Kalman filter [Sakaguchi et al., *Space Weather*, 2013, 2015]. These models also give us some clue for understanding RB dynamics.
- GEO MeV electron flux data from the Japanese HIMAWAEI-8 metrological satellite is available for the real-time monitoring since November 2014. Data will be provided from NICT soon.

Radiation Belt Electron Forecast Web

<http://seg-web.nict.go.jp/radi/en/>

The screenshot shows the main interface of the Radiation Belt Electron Flux Forecast website. At the top, there is a navigation menu with options like 'Top', 'Hazard Map at GEO', 'Observation Data Box', 'Forecast Performance', 'Electron Flux Variation', 'About This Site', and 'What is the Radiation Belt?'. Below the navigation, there are two introductory cards: 'About This Site' and 'What is the Radiation Belt?'. The main content area is divided into several sections:

- Electron Flux Forecast:** A large section showing the current status. It features a large yellow circle with the NICT logo and the word 'High'. Below it, it states 'Today 2015/09/14' with a daily average of 1584 $(\text{cm}^2 \text{sr s}^{-1})$ and a daily maximum of 9120 $(\text{cm}^2 \text{sr s}^{-1})$. It also shows forecasts for 'Tomorrow' (Quiet) and 'The Day After Tomorrow' (Quiet).
- Event Information:** A red box containing text about a solar proton event on 2015/09/14, mentioning a GOES solar proton event and its impact on the radiation belt.
- Event back number (Japanese Only):** A section for historical event data.
- Daily report (Japanese Only):** A section for daily reports.
- Description of Symbols:** A legend for the forecast symbols: Quiet ($< 1,000 \text{ cm}^2 \text{sr s}^{-1}$), High ($\geq 1,000 \text{ cm}^2 \text{sr s}^{-1}$), and Extreme ($\geq 10,000 \text{ cm}^2 \text{sr s}^{-1}$).
- Announce:** A section for news or announcements.
- Observation Data Box:** A section for real-time data plots.
- Hazard Map at GEO:** A section for hazard maps.
- Forecast Performance:** A section for performance metrics.
- Time History of Electron Flux Variation:** A section for historical data.

The screenshot shows the 'Hazard Map at GEO (geostationary earth orbit)' page. It features a line graph showing the 2 MeV electron flux distribution from 2015/09/14 to 2015/09/16. The y-axis is labeled '>2MeV electron flux ($\text{cm}^2 \text{sr s}^{-1}$)' and ranges from 10^0 to 10^6 . The x-axis shows time in hour:minute (MLT) from 00:00 to 15:00. The graph displays observation data (GOES/Secondary) as a blue line, a forecast as a red line, and a blue shaded area representing the forecast error range (Standard deviation $\pm 1 \sigma$). Below the graph, there is a section for 'Open Observation Data Box' and a 'Local time hazard map at GEO' section. The hazard map section includes a 'Change plot date' button (Yesterday, Today, Tomorrow) and a 'Show your satellite position' section where a user can enter a longitude (e.g., 135) and a star sign will appear on a circular diagram of the GEO orbit. The diagram shows the positions of various satellites: Japan's present location (J), MITSAT-2 (MITSAT-2), GOES/Primary (O), and the user's input (I). The orbit is divided into 12MLT, 06MLT, and 18MLT segments. A legend on the right identifies the symbols for Quiet (green), High (yellow), and Extreme (red).



Thank you for attention

