Real-Time Estimation of Astronaut Doses During Large Solar Particle Events Based on WASAVIES

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• Background & Outline

• Development of WASAVIES
  ✓ Calculation procedure
  ✓ Validation
  ✓ Results of dose calculation

• Development of WASAVIES-EO
  ✓ Calculation procedure
  ✓ Validation
  ✓ Results of dose calculation

• Summary
Evaluation of cosmic-ray fluxes in the magnetosphere

- Risk of astronauts in spacecrafts due to radiation exposure
- Soft-error rates of semi-conductor devices loaded on satellites

Sources of cosmic-rays

- Galactic cosmic-ray (GCR)
- Trapped particle (TP)
- Solar energetic particle (SEP)

Rather stable and predictable
(DLR model, BO model, AP-9 etc.)

Hardly predictable in the mission design stage

- Worst-case scenarios (Xapsos et al. 1999 etc.)
- Post-exposure evaluation (Hu et al. 2016, Matthiä et al. 2018)
- Real-time estimation (Mertens et al. 2018)
- Forecast (No method is available)
Outline of Developing Model

1. Download GOES proton flux & several NM count rates by every 5 min
2. Check the occurrence of Ground Level Enhancement (GLE)
   - Yes
3. Determine 4 parameters that characterize the event profile
4. Nowcast & forecast the radiation doses in the atmosphere

Warning System for AVIation Exposure to SEP (WASAVIES)

- Nowcast & forecast SEP & GCR fluxes on certain Earth orbits
- Nowcast & forecast astronaut doses in satellites on the orbits

WASAVIES for Earth Orbit (WASAVIES-EO)
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How to Estimate SEP Dose?

Precise Estimation
• Interplanetary space: 3D MHD simulation for each event
• Magnetosphere: Proton trace simulation with dynamic MF model
• Atmosphere: Monte Carlo airshower simulation

too time consumptive & complicated

WASAVIES
We developed databases based on…
• 1D focused transport equation from the Sun to the Earth
• Proton trace simulation inside magnetosphere with static MF model
• Airshower simulation for mono-energetic SEP incidence

IP, γ, θ_p, N_0 are automatically determined during GLE in real time
Flowchart of WASAVIES

Automatically download by every 5 min

GOES proton fluxes above 100 MeV: $\Phi_{\text{GOES}}$

GLE occurs? - Yes

Calculate relative count rates of NM, $C_{n,IP,\gamma,\theta_t}$, at each station for all IP, $\theta_t$, $\gamma$

Evaluate best-fit $N_0$ to reproduce current NM count rates for each IP, $\theta_t$, $\gamma$

Evaluate best-fit IP & $\theta_t$ for each $\gamma$ to reproduce past & current NM count rates

Evaluate best-fit $\gamma$ to reproduce current $\Phi_{\text{GOES}}$, using evaluated IP, $\theta_t$, $N_0$

Nowcast & forecast SEP dose rates in the atmosphere, $D_j(t,h)$

Count rates of 13 neutron monitors

End of a day - Yes

Calculate force-field potential of the day

Nowcast GCR dose rates in the atmosphere

1-D focused transport equation

Anti-proton trace model with Tsyganenko-89

SEP fluxes at 1 AU, $\Phi_{1\text{AU},IP,\gamma}(t, E_0, \phi)$

Probability density of pitch angle, $P_{G.0,Kp,\theta}(E_0, \phi)$

Response function of airshower simulation, $R_{\text{EAS},i}(E_0, E_i, h)$

Response function of NM, $R_{\text{NM},i}(E_i)$

Particle and heavy ion transport code system: PHITS

Effective dose conversion coefficient, $R_{\text{ED},i}(E_i)$

GCR model PARMA
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Event Selection

For reliable benchmark of SEP model ...

- Flare events associated with large GLE
- GOES high-energy proton flux data must be available (1998~)

Profiles of analyzed events

<table>
<thead>
<tr>
<th></th>
<th>GLE60</th>
<th>GLE69</th>
<th>GLE70</th>
<th>GLE71</th>
<th>GLE72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flare class</td>
<td>X14.4</td>
<td>X7.1</td>
<td>X3.4</td>
<td>X5.1</td>
<td>X8.2</td>
</tr>
<tr>
<td>Date, Year</td>
<td>Apr 15, 2001</td>
<td>Jan 20, 2005</td>
<td>Dec 13, 2006</td>
<td>May 17, 2012</td>
<td>Sep 10, 2017</td>
</tr>
<tr>
<td>Maximum NM</td>
<td>~200%</td>
<td>~2000%</td>
<td>~90%</td>
<td>~15%</td>
<td>~15%</td>
</tr>
<tr>
<td>increase rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anti-isotoropy</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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</tbody>
</table>
Comparison between measured and calculated count rates of some NM stations

Good agreement!!
Comparison between measured and calculated GOES proton fluxes (E>100MeV)

Validation with Flight-Dose Measurements

Dose rates in two flights (Frankfurt–Dallas & Prague–New York) during GLE 60

WASAVIES can reproduce the experimental data very well!

(A) FRA–DFW
- Dose rate (ACREM)
- Dose rate (cal., $D_{air} + 2 \times E_{GCR-neutron}$)
- Dose rate (cal., $D_{air}$)
- Altitude

(B) PRG–JFK
- Dose rate (LIULIN)
- Dose rate (cal., $D_{air}$)
- Altitude

Bartlett et al. (2002)
Spurny and Dachev (2002)
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Dose Rate at Conventional Flight Altitude

Comparison of GCR and SEP dose rates at the highest dose locations at 12 km

- $D_{\text{SEP}} > D_{\text{GCR}}$ at the beginning of GLE 60 & 69
- $D_{\text{SEP}} < D_{\text{GCR}}$ during entire GLE 70 → Safety of aircrews due to SEP exposure
Dose Rate Map at the Peak of GLE69

Calculated SEP Dose Rate at 7 AM on Jan. 20, 2005 at 12 km

- North–South asymmetry is clearly observed
- Dose estimation based only on cut–off rigidity is not accurate enough
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Flowchart of WASAVIES-EO

GOES proton fluxes above 100 MeV: $\Phi_{\text{GOES}}$

Automatic download at intervals of 5 min

Count rates of 13 neutron monitors

GLE occurs? Yes

Calculate best-fit IP, $\theta_t$, $\gamma$, and $N_0$

Calculate SEP fluxes and dose rates in the atmosphere, $D_j(t,h)$

Calculate probability density of pitch angle, $P_{S,Kp,\theta}(E_0, \phi)$ for best-fit $\theta_t$

Calculate SEP flux outside satellite, $\Phi_{\text{SEP,SOul}}(t_c,E_0)$

Calculate SEP flux inside satellite, $\Phi_{\text{SEP,Sin}}(t_c,E_0)$

Calculate SEP dose rates inside satellite, $D_{\text{SEP,Sin}}(t_c)$

GCR mode

End of a day

Yes

Calculate force-field potential of the day

Calculate GCR fluxes and dose rates in the atmosphere

Calculate GCR fluxes at 1 AU, $\Phi_{\text{GCR,1AU}}(E_j)$

Calculate geomagnetic transmission function, $T_{S,Kp,j}(t_c,E)$

Calculate GCR flux outside satellite, $\Phi_{\text{GCR,SOul}}(t_c,E_0)$

Calculate GCR flux inside satellite, $\Phi_{\text{GCR,Sin}}(t_c,E_0)$

Calculate GCR dose inside satellite, $D_{\text{GCR,Sin}}(t_c)$

Calculate GCR model in the atmosphere: PARMA

Effective dose conversion coefficient, $R_{\text{ED,}(E)}$

GCR model at 1 AU developed by DLR

TLE data of satellite

Particle trace model based on Tsyganenko-89

1-D focused transport equation

Kp

SEP fluxes at 1 AU, $\Phi_{1\text{AU,IP},j}(t,E_0,\phi)$

Probability density of pitch angle, $P_{G,O,Kp,\theta}(E_0,\phi)$

Response function of EAS simulation, $R_{\text{EAS,}(E_0,E_i,h)}$

Response function of NM, $R_{\text{NM,}(E)}$

Particle and heavy ion transport code system: PHITS

Response function for converting particle fluence to various kinds of doses, $R_{D_i}(E_i)$

Response function of particle fluence in satellite, $R_{S_j}(E_j, E_i)$

Blue line: used for the original WASAVIES
Red line: newly implemented for WASAVIES-EO

WASAVIES–EO starts after all analyses of WASAVIES are finished, based on TLE data
Virtual ISS model developed by JAXA

- Manually constructed from 2D CAD data (different from Goto-san’s one)
- Experimental racks in the Kibo module are reproduced
- Other modules are simply reproduced by their shapes and masses
- Mean shielding thickness in the pressurized module of Kibo is 35.6 g/cm²
- Response functions in 16 locations in the Kibo module are calculated
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WASAVIES–EO can reproduce GCR dose rates very well
- SAA peaks are not reproduced because TP contribution was not considered
- $D_{\text{cal}} < D_{\text{exp}}$ slightly at the SEP peak $\rightarrow$ difference of shielding configuration

*D Reitz et al. 2005, Berger et al. 2018*
Dose rates measured by Si detector (Liulin-5) in MATROSHKA-R phantom in Russian module of ISS

- Dose rates were increased only to some extent by SEP
- Slight increase of the dose rates are well reproduced by WASAVIES–EO

*Semkova et al. 2014*
DOSTEL in Columbus

Dose rates measured by Si detector (DOSTEL) in ISS Columbus module

- $D_{cal} > D_{exp}$ at the SEP peak $\rightarrow$ difference of shielding configuration or overestimation of low-energy SEP fluxes ($E<80\text{MeV}$)

*Berger et al. 2018
Proton fluxes measured in POES

Proton fluxes above 100 MeV measured in POES satellite during GLE 72

WASAVIES–EO can reproduce the data except for early stage

Applicable to not only ISS but also other satellites
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Nowcast radiation doses

Effective dose at flight altitude and astronaut dose equivalent in ISS during GLE 69 and 70

GLE69

GLE70

Peak of astronaut doses does not always much with GLE peak

GLE 70 occurred at the worst timing
Forecast radiation doses

The same data, but forecasted at 20 min after GLE detection

Time structure agree with nowcast data very well

Useful for mission operation such as evacuation to radiation shelter.

GLE69
- Effective dose at flight altitude (µSv/h)
- RBM dose equivalent in ISS (µSv/h)
- RBM dose in ISS (µGy/h)

GLE70
- Effective dose at flight altitude (µSv/h)
- RBM dose equivalent in ISS (µSv/h)
- RBM dose in ISS (µGy/h)
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• Summary
✓ WASAVIES-EO was developed for nowcasting and forecasting the GCR and SEP fluxes inside and outside any satellites on Earth Orbit

✓ The accuracy of WASAVIES-EO, was well validated by dose rates measured in ISS & high-energy proton fluxes observed by POES

✓ Web-interface of WASAVIES is currently under development, and that of WASAVIES-EO will be developed later
Website of WASAVIES for issuing SEP exposure alert via NICT server
Basic features of WASAVIES

Application of WASAVIES to GLE72

Basic features of WASAVIES-EO
To be submitted within a week or so