Dose Calculation inside Kibo Using PHITS and ISS 3D-CAD Geometry

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Future human missions and radiation protection

  (ISECG: International Space Exploration Coordination Group)

⇒ Radiation protection technology is required!
Accurate estimation of exposure dose

“Radiation Protection Technology”

- Accurate estimation of exposure dose
- Optimization of shielding design

Our final goal: Establishment of “Exposure-Dose Estimation Method” for operating actual future missions!

Computer simulation using radiation transport code

To estimate dose using computer simulation for an ACTUAL mission ….

<Needed to evaluate>
- Accuracy of a transport code and radiation environment models
- Appropriate setting of a calculation geometry
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This work

**Dose calculation inside JEM**

- Using
  1) PHITS code**
  2) Existing radiation environment models
  3) ISS or JEM 3D-CAD model

**Dose measurement inside JEM**

- Area monitoring data inside JEM obtained by Area PADLES*** passive dosimeters

We evaluated the accuracy of radiation environment models and the appropriate setting of calculation geometry.

* JEM: ISS Japan Experiment Module “Kibo”
** PHITS: Particle and Heavy Ion Transport System (Monte Carlo calculation code)
*** PADLES: Passive Dosimeter for Lifescience Experiments in Space

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Geometric: 3D-CAD model

- 3D-CAD model (.stp): UG NX 8.0
- Converting CAD files (.stp) to PHITS input format: SuperMC 3.2.0

**SuperMC** (Super Monte Carlo Program for Nuclear and Radiation Simulation)
- Free software for radiation transport calculation
- Developed by Institute of Nuclear Energy Safety Technology, China
- Convert CAD file format to some transport code input formats (PHITS, Geant4, FLUKA, MCNP)

- **ISS partial model**
  - Modules: JEM, Node 1~3, U.S.Lab, Columbus, PMM
  - Other structures: Truss structures, Cupola, Airlock (Quest), PMA

- **Modules (except JEM) and other structures**
  - Simplified geometry (e.g. module -> homogeneous cylinder)
  - Composed of Al
  - Mass of each structure: the same as that of the actual structure (adjusting the density of Al)
Geometry: JEM model

- **JEM model**
  - PM, ELM-PS, EF
  - Node 2

- **ELM-PS, EF**
  - Including outer shell structure, debris bumpers, system and experimental racks, JEM airlock (not including robotic arm)

- Composition of each structure: A2219, A6061, A7075, Al (+ Air)
- Mass of each structure: the same as that of the actual structure (adjusting the density of materials)
Geometry: JEM model (t-3dshow)
Geometry: Virtual PADLES dosimeters

- Virtual PADLES dosimeters (x 17): Installed on the same position as actual PADLES dosimeters

<table>
<thead>
<tr>
<th>Virtual PADLES dosimeters</th>
<th>Actual PADLES dosimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Virtual PADLES dosimeter diagram" /></td>
<td><img src="image" alt="Actual PADLES dosimeter diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CR39 (C₁₂H₁₈O₇)</th>
<th>CR39, TLD</th>
</tr>
</thead>
</table>

: PM  : ELM-PS
Geometry: Mean shielding thickness (Ray-tracing)

- Mean shielding thickness of the ISS/JEM model from virtual PADLES dosimeters (x 17) was calculated by ray-tracing.

- Calculated mean shielding thickness
  - ISS model: 29 ~ 72 g/cm²
  - JEM model: 24 ~ 62 g/cm²

- Near Node 2: higher shielding thickness
- Near EF and inside ELM-PS: lower shielding thickness
- Use the same method developed by our previous study
- GCR: Matthiä model, Trapped proton: AP8 model
- East-west effect (deviation of trapped proton at SAA): 0.5 or 0

Radiation source: Radiation environment models

- Orbit data (TLE) → Original coordinate conversion program → Altitude, latitude, longitude → Trapped proton model: AP8* → Trapped proton fluxes on the orbit
- Year, month, day → Geomagnetic activity index: Kp → Original proton trace model in the magnetosphere
- GCR model developed by Matthiä et al. → GCR fluxes at 1 AU → GCR fluxes on the orbit

Solar modulation potential

Geomagnetic transmission function

GCR fluxes on the orbit

Information provided by users

Calculated quantity

External database or model taken from literature

Original model

Use the data of “Area PADLES #14 and #15” for determining $K_p$ index and solar modulation potential

<table>
<thead>
<tr>
<th>Area PADLES #14</th>
<th>Launch</th>
<th>Return</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/3/28 (Soyuz TMA-16M)</td>
<td>2015/9/12 (Soyuz TMA-16M)</td>
<td>169 days</td>
<td></td>
</tr>
<tr>
<td>Area PADLES #15</td>
<td>2015/9/2 (Soyuz TMA-18M)</td>
<td>2016/3/2 (Soyuz TMA-18M)</td>
<td>183 days</td>
</tr>
</tbody>
</table>

Mean altitude of the ISS

Solar activity (F10.7)*

* JAXA Space Environment & Effects System: SEES, Ver.100 (Aug, 2018)
Dose calculation and computer

- PHITS Ver.: 3.03

- **Absorbed dose** (D) and **dose equivalent** (DE)* in virtual PADLES dosimeters were calculated.

  *DE: D x Q(L) (Q(L): given in ICRP Publication 60)

- **Computer**: JAXA Supercomputer System Generation 2 (JSS2), Pre-Post System (SORA-PP)
  - Core: 120 (12 Core x 10 Node)
  - Memory: 50 GB/Node
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Results: Area PADLES #14

Absorbed dose (D)  
Dose equivalent (DE)

Ratio of Calc. dose to Exp. dose

Error bar of calculated data:  
Statistical error (S.D.) of Monte Carlo calculation

Calc. D and DE are in agreement with Exp. Doses within ~20% and ~30%, respectively!
Results: Area PADLES #15

Absorbed dose (D)  Dose equivalent (DE)

Error bar of calculated data:
Statistical error (S.D.) of Monte Carlo calculation

Ratio of Calc. dose to Exp. Dose

C/E (D)  C/E (DE)

No.17: Discrepancy of geometry!

Calc. D and DE are in agreement with Exp. Doses within ~20% and ~30%
respectively!

AP8, Matthiä model; PHITS; ISS/JEM model
-> Enough accuracy!
### Results: Area PADLES #14/#15

- **Mean ratio (C/E) of the calculated dose (C) to the experiment dose (E)**

\[
\overline{C/E} = \frac{1}{17} \sum_{i=1}^{17} \frac{C_i}{E_i}
\]

(Err. (S.D.): \( \sigma = \sqrt{\frac{1}{17} \{(C_i / E_i)^2 - (\overline{C/E})^2\}} \))

#### Table: Area PADLES #14/#15

<table>
<thead>
<tr>
<th>Area PADLES</th>
<th>D or DE</th>
<th>EastWest</th>
<th>ISS model</th>
<th>JEM model</th>
</tr>
</thead>
<tbody>
<tr>
<td>#14</td>
<td>D</td>
<td>0.5</td>
<td>1.07±0.22</td>
<td>1.13±0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1.09±0.25</td>
<td>1.14±0.24</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>0.5</td>
<td>1.17±0.24</td>
<td>1.21±0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1.18±0.26</td>
<td>1.22±0.26</td>
</tr>
<tr>
<td>#15</td>
<td>D</td>
<td>0.5</td>
<td>1.07±0.28</td>
<td>1.14±0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1.09±0.30</td>
<td>1.15±0.31</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>0.5</td>
<td>1.24±0.33</td>
<td>1.30±0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1.25±0.34</td>
<td>1.31±0.35</td>
</tr>
</tbody>
</table>

- **Mean C/E**
  1) East-west effect: 0.5 < East west effect: 0  
  2) ISS model < JEM model  

-> The difference is little!

- Considering a time efficiency, the detail geometry data is NOT necessarily.
- It is important to use a geometry reproducing the surrounding shielding environment of the position where estimated an exposure dose.
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Summary

- Using the ISS (partial) and JEM 3D-CAD models, existing radiation models, and PHITS code, the doses in JEM were calculated, and compared with the measured data.

- **Radiation Environment Models:** The calculated doses are in agreement with the measured data mostly within \(~20\%\) and \(~30\%\) for D and DE, respectively. This result suggests that the estimation of doses using AP8, Matthia model, PHITS, and ISS/JEM model has an enough accuracy.

- **Geometry:** For an accurate estimation of an exposure dose, it is important to use a geometry reproducing the surrounding shielding environment of the position where estimated doses.

Future works

- Calculations using AP9 and the radiation models in other period

- Detail evaluation of the accuracy of the trapped proton and GCR models by the comparison between calculated doses and measured doses by an active sensor.