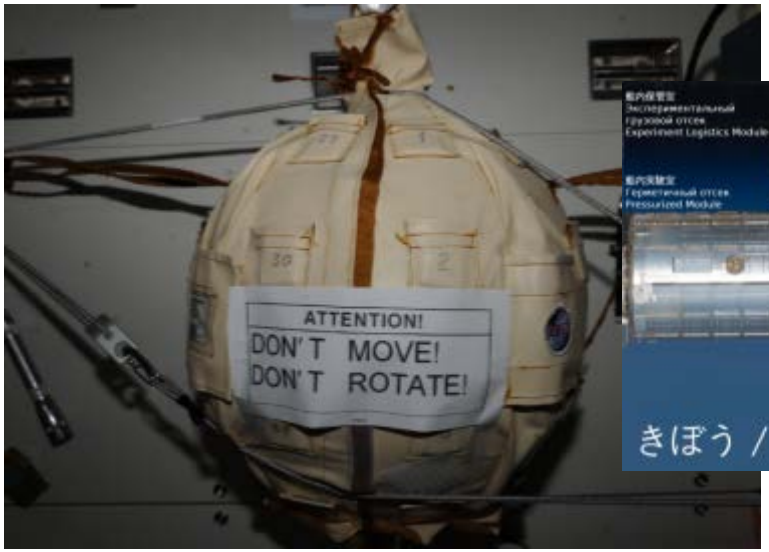
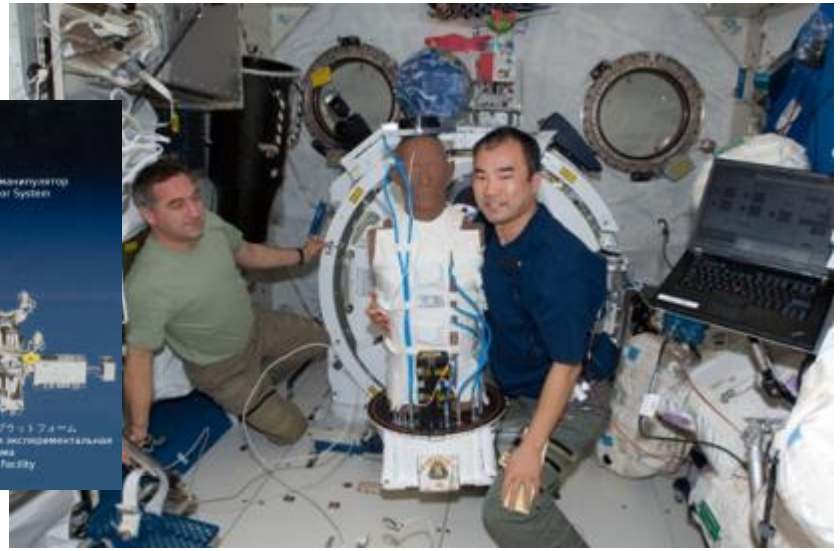
Comparative study between Radiation Doses in the MATROSHKA Anthropomorphic Phantom and he Matoroshka-R Spherical phantom Experiment#1 aboard International Space Station 'KIBO'





Aiko Nagamatsu[1]*, Tatsuhiko Sato[2], Keiichi Kitajo[3], Ken Shimada[3], Kazuo Takeda[4], Nakahiro Yasuda[1], Tsusyoshi Ito[1], Igor Nikolaev[5], Raisa Tolochek[6], Vyacheslav Shurshakov[6], Thomas Berger[7], and Gunther Reitz[7]

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3. Advanced Engineering Services Co., Ltd, Ibaraki, Japan
4. Research Organization for Information Science and Technology, Ibaraki, Japan.
5. S.P. Korolev Rocket and Space Corporation (RSC-Energia)
6. Institute of Biomedical Problems (IBMP), Radiation Safety Department
7. DLR, Cologne, Germany

PADLES（Passive Dosimeter for Life science Experiments in Space ）

TLD MSO-S: Thermo Luminescence Dosimeter

(MSO-S; Kasei Optonics industry)

Mg_2SiO_4 : Tb powder enclosed in a Pyrex glass test tube with Ar gas

CR-39 PNTD: Plastic nuclear track detectors

(HARZLAS TD-1; Fukuvi Chemical industry)

Allyl diglycol carbonate polymer doped with anti oxidant (0.1wt% NAUGARRD)

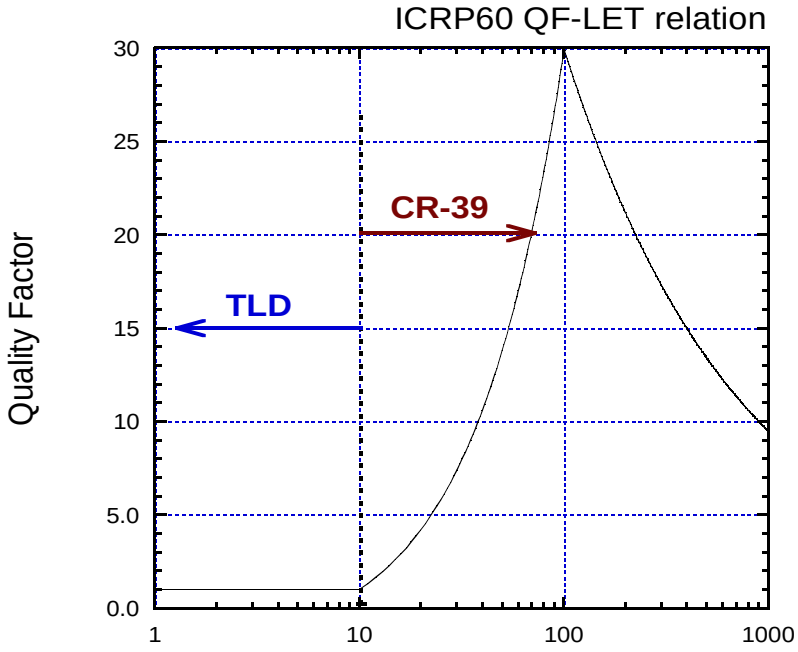
■ Total absorbed dose : D_{TOTAL} （Gy-water）

$$
\begin{aligned}
&D_{TOTAL} \\
&= D_{\leq 10keV/\mu m-water} + D_{>10keV/\mu m-water} \\
&= (D_{TLD} - \kappa D_{CR-39}) + D_{CR-39} \\
&= D_{TLD} + (1-\kappa) D_{CR-39}
\end{aligned}
$$

■ Total dose equivalent : H_{TOTAL} (Sv)

$$
\begin{aligned}
&H_{TOTAL} \\
&= D_{\leq 10keV/\mu m-water} + H_{>10keV/\mu m-water} \\
&= (D_{TLD} - \kappa D_{CR-39}) + H_{CR-39}
\end{aligned}
$$

κ : mean TL efficiency for LET above 10 keV/μm



CR−39 measures a LET distribution of particle fluence ≥ 10 keV/μm

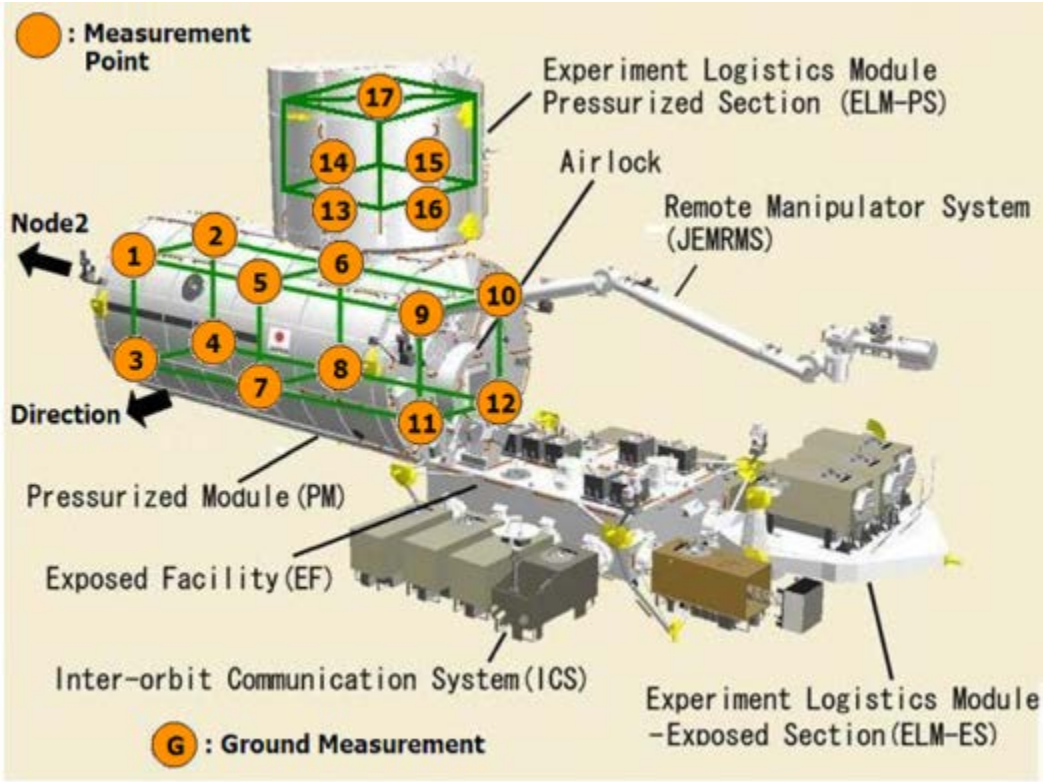
T. Doke et al. (1995); Estimation of dose equivalent in STS-47 by a combination of TLDs and CR-39. Radiat. Meas. 24, 75-82.

A. Nagamatsu et al.,(2006), (2009), (2011), (2013)

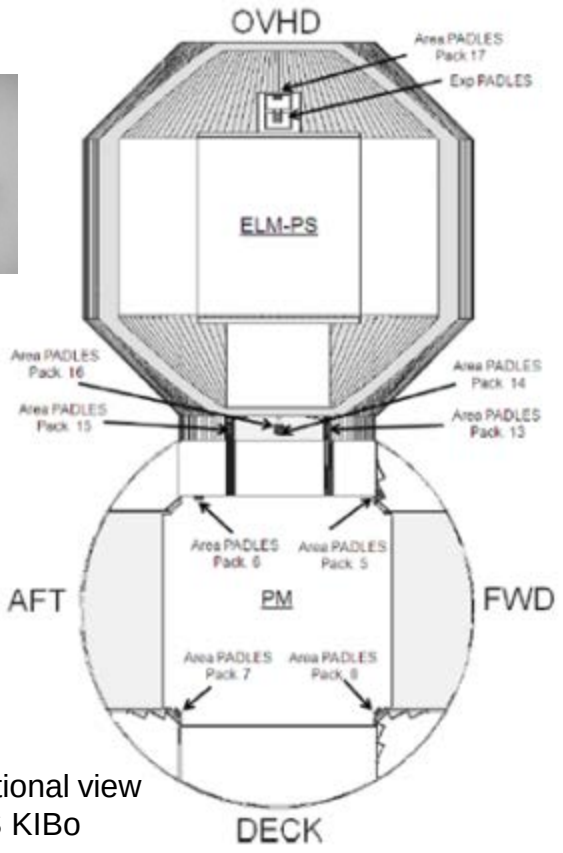
H. Tawara et al., (2008), (2011)

Area PADLES - Area Monitoring from 1J（Inc17), June 2008

- Area monitoring aims to perform a survey of the radiation environment at 17 fixed locations inside the KIBO by Area PADLES.
- The dosimeters are replaced every increment throughout the KIBO program.
- The Shielding thickness of the monitoring points are relatively thin.
- Orientation: Perpendicular to Earth- Pack 1 - 4, 9 -13 and 16
  Parallel to Earth- Pack 6 and 17
  angle of 45 degrees – Pack 5, 7 and 8



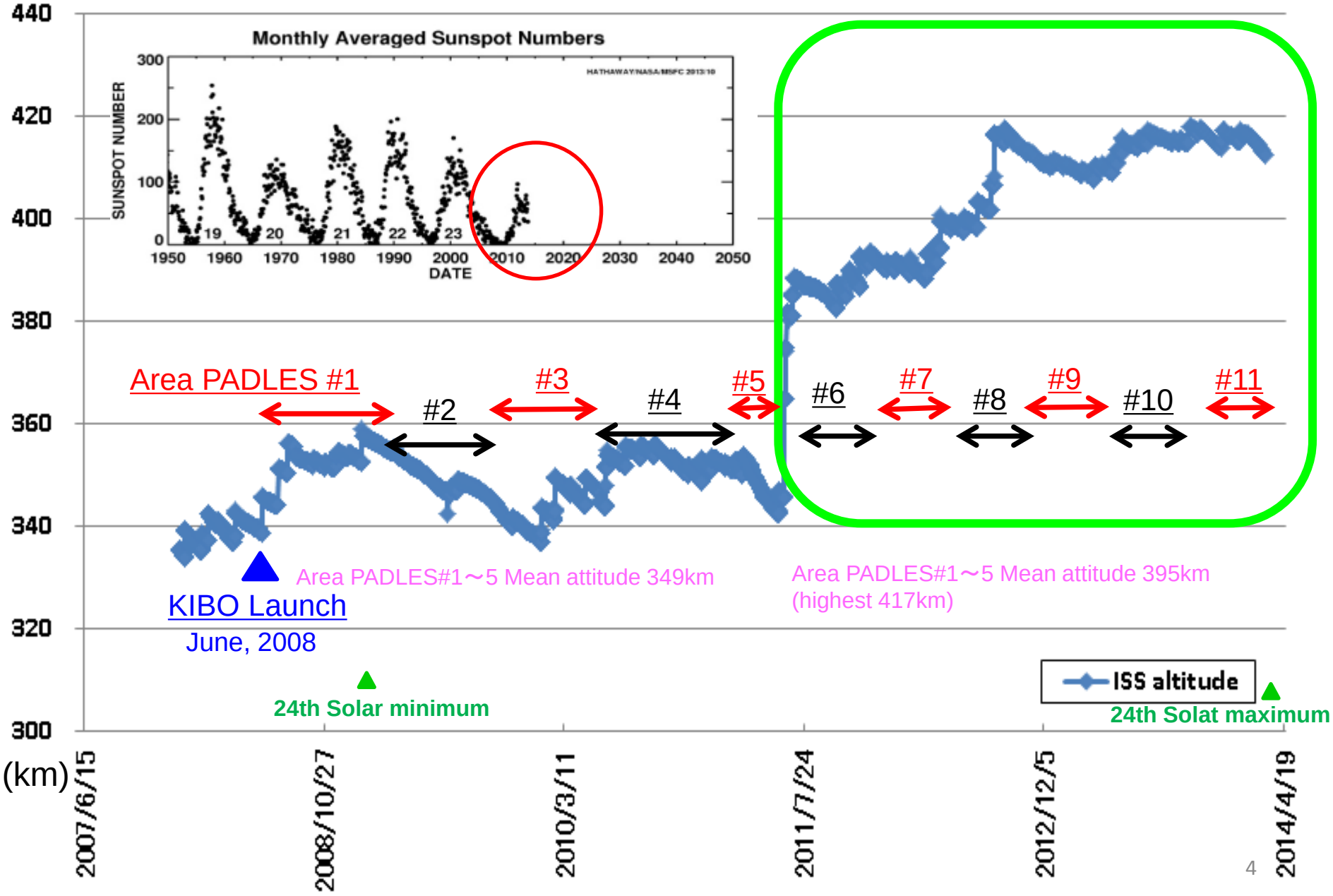
Area PADLES dosimeter



Cross Sectional view of ISS KIBo

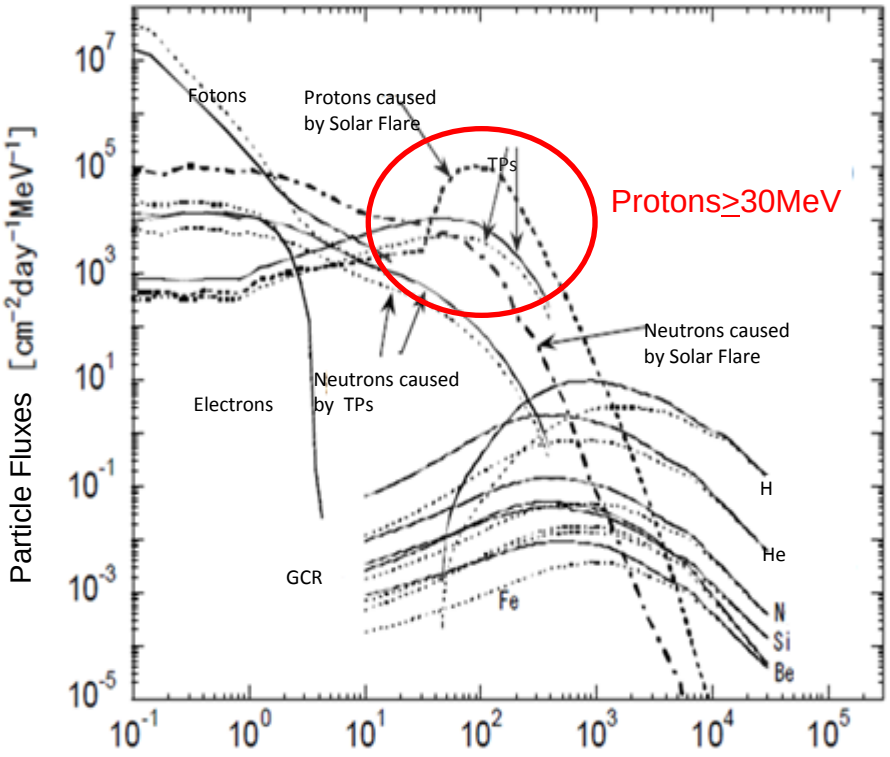
ISS Attitude change from 2008 tto 2013

2014 JSAP presentation

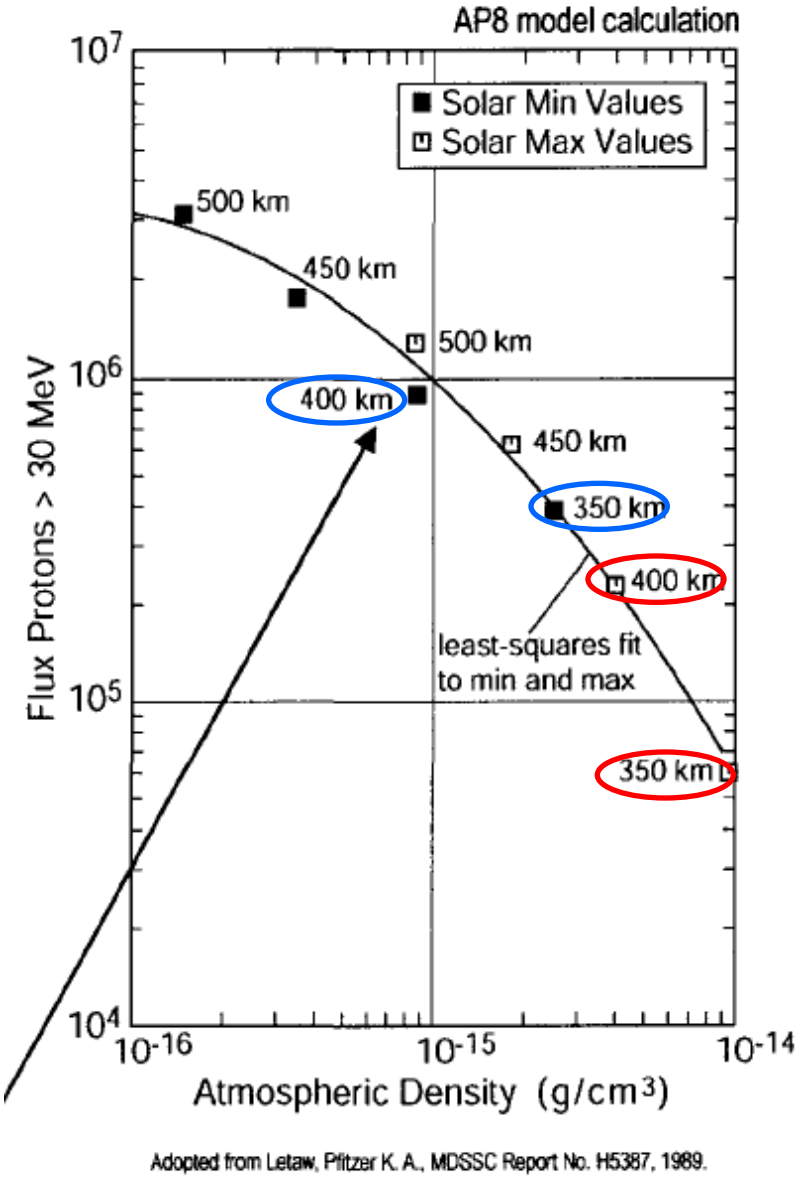


Proton Particle Fluxes changes depending on the ISS Attitude caluculated estimated by AP8 model

Particle Fluxes changes
two times in solar min,
four times in solar max,
due to ISS attitude changes abuut 50 km.



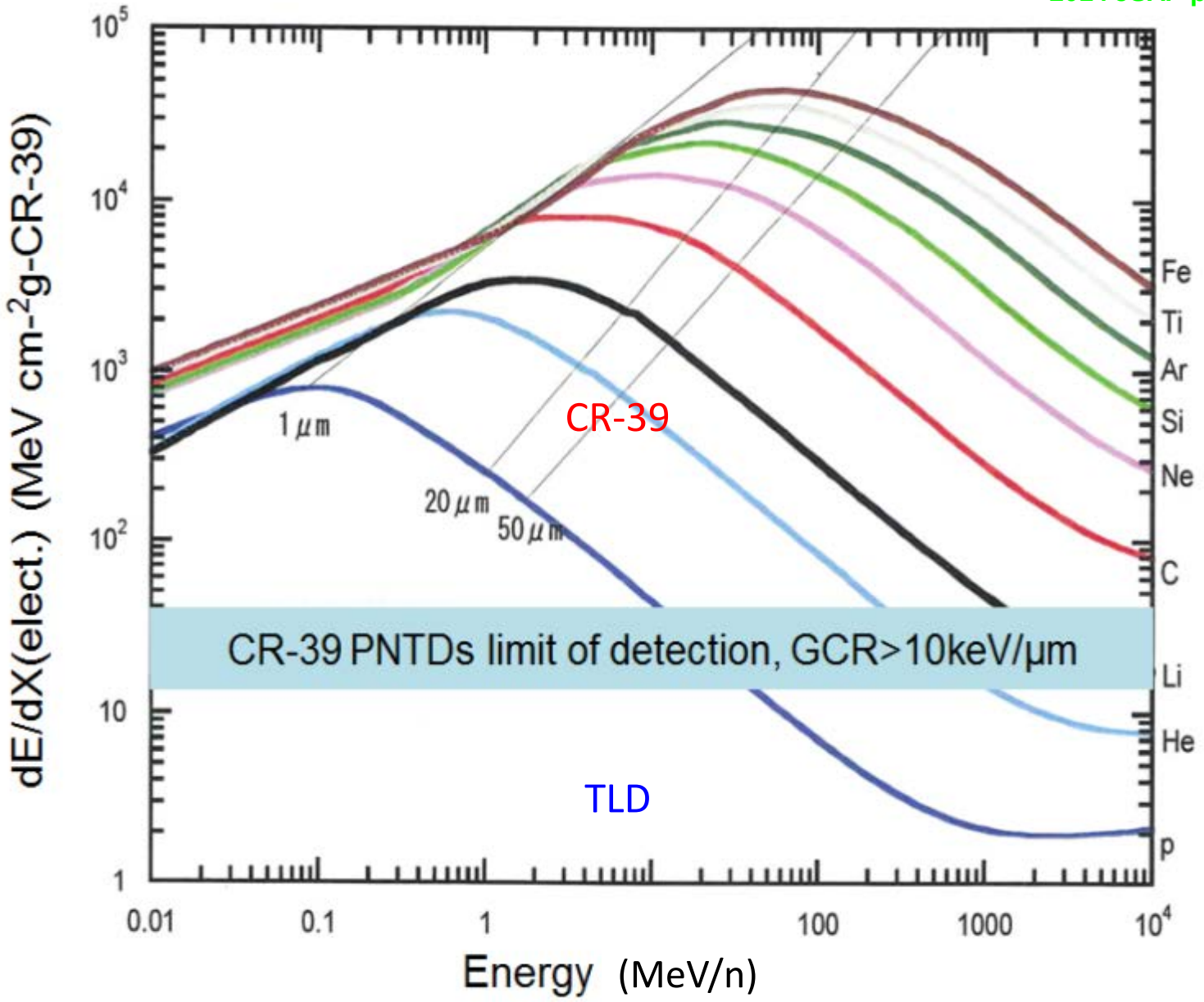
Particle Fluxes of various space radiation particles inside the ISS at an Attitude of 407.44km, the inclination of orbit is 51.6 degrees. The ISS module hull has an 9.5mm thick film of aluminum.



Adopted from Letaw, Pfitzer K. A., MDSSC Report No. H5387, 1989.

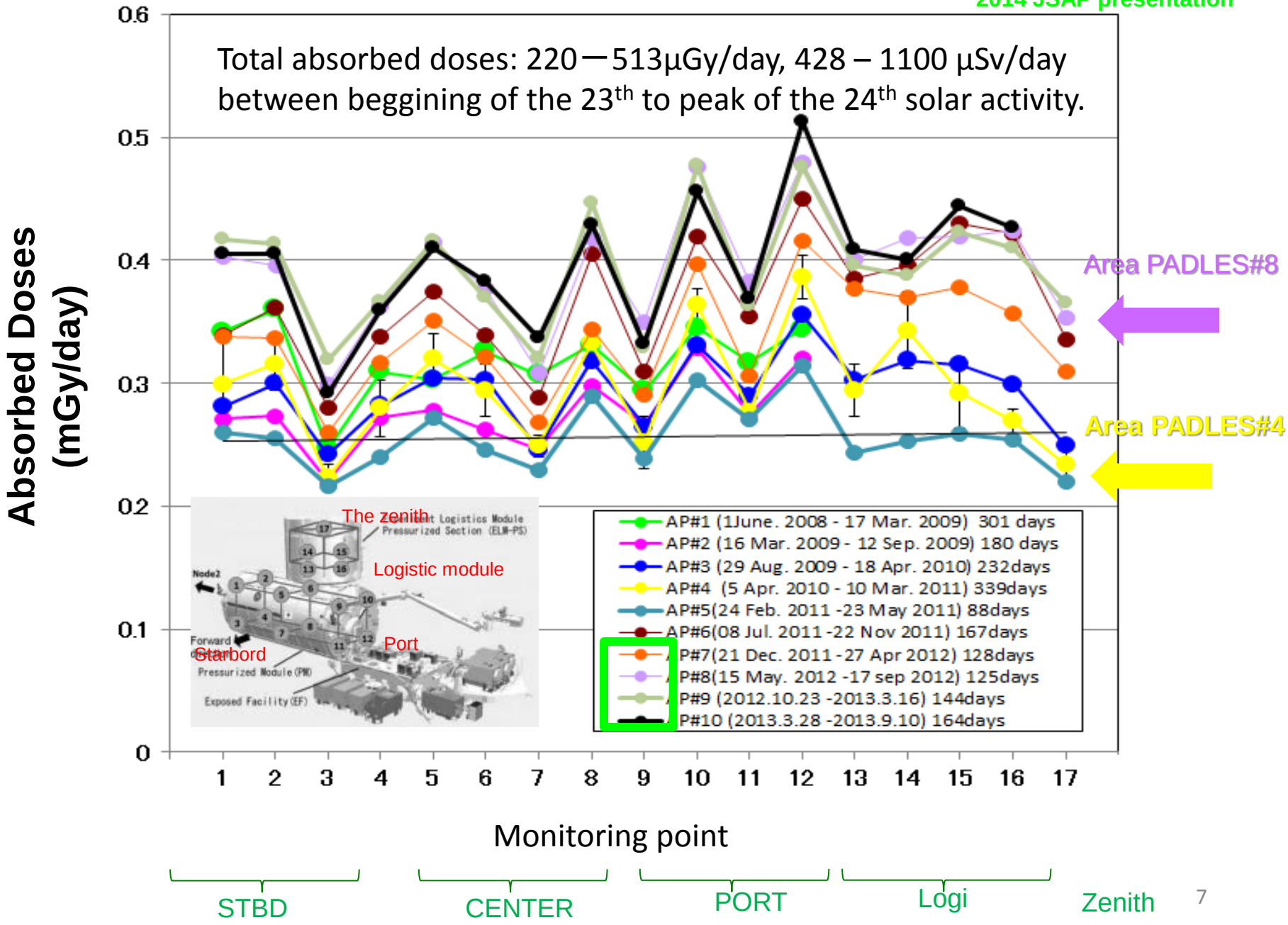
Energy range for charged particles measured by PADLES

2014 JSAP presentation



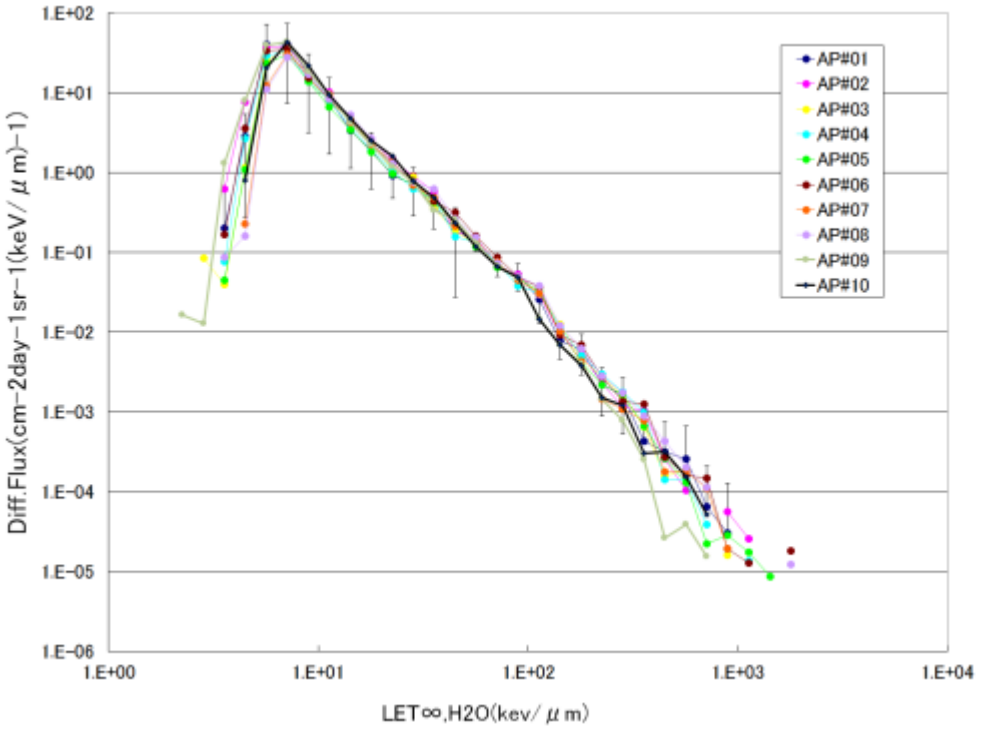
Results of Area PADLES #1-10 (June 2008 to Sep. 2013 over 5 years)

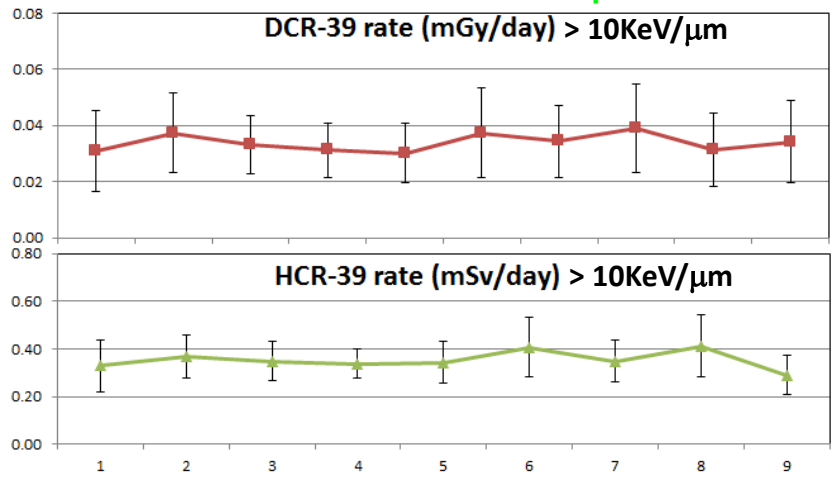
2014 JSAP presentation

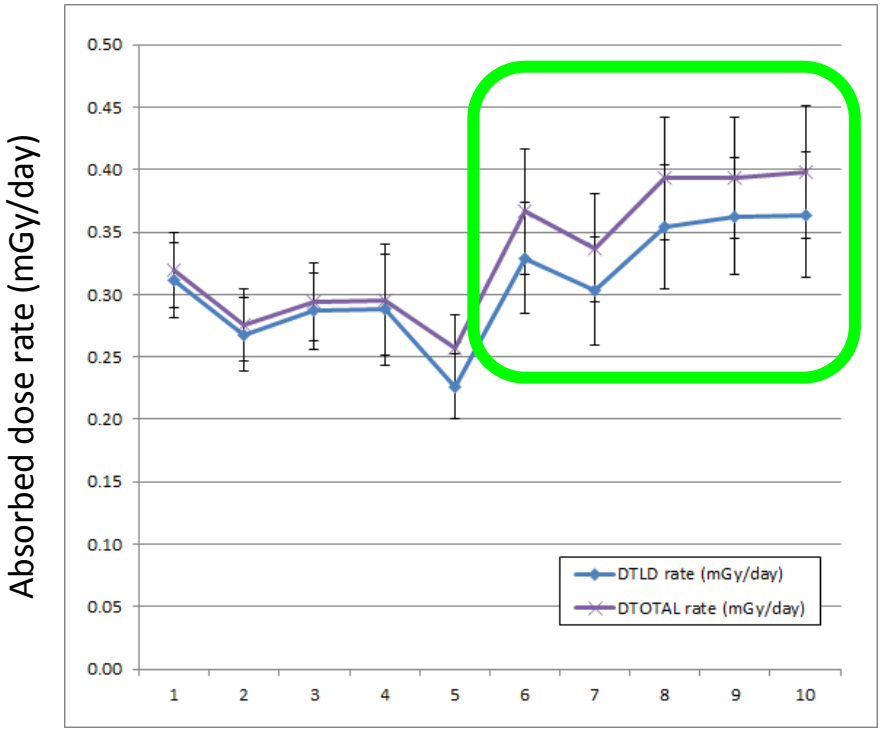


Area PADLES#1-10 Averaged LET distributions and doses

2014 JSAP presentation







- Over Increment 17 to 36, June 2008 - Sep., area radiation monitoring in previous 10 experiments with Area PADLES were conducted during the solar minimum at the end of the 23rd to the maximam of the 24th solar cycle.
- Averaged LET distributions, D_{cr-39} and H_{cr-39} ＞ 10keV/μm（GCR）obtaind from CR-39 PNTDs in each experiments didn't change so much.
- Absorebed doses ＜10keV/μm increased with an increase in ISS altitude remarkably.

Area PADLES experiment No. #1 to 10

Construction of Virtual ISS KIBO (Average thickness is 27.21 g/cm^2)

This study are expected to:

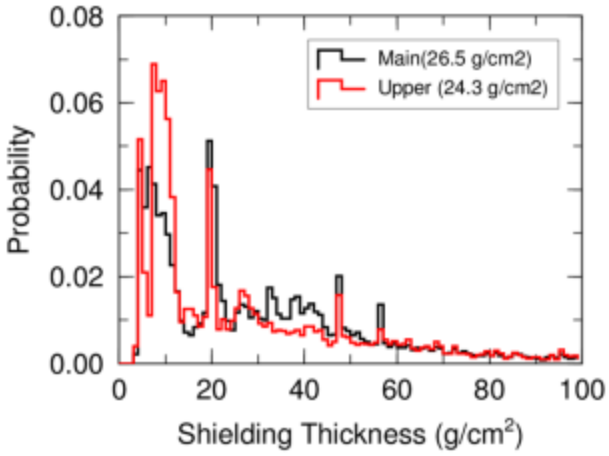
- Contribute to risk assessments of astronauts on space flights
- Feasibility study for effective shielding materials and thickness

Kibo geometry model:

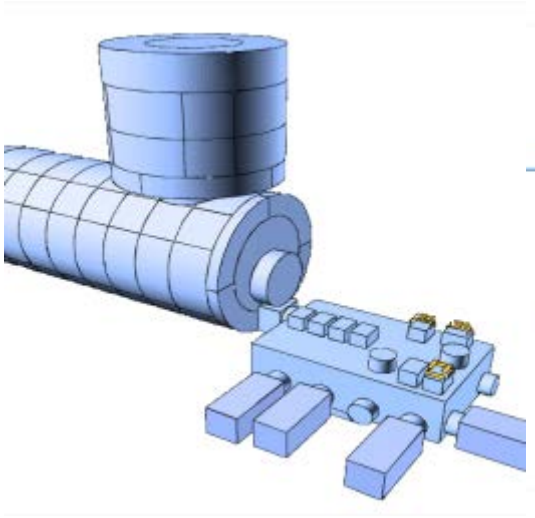
- Kibo: Cylindrical shape with the thickness (9.7-15.1 g/cm^2 in water equivalent) mainly consists of hull wall（A2219, 4.8mm^t）and debris bumper（A6061, 1.27mm^t）
- The mass and volume of main body with all 23 racks and the densities are well presented based on flight information.
- Virtual KIBO was created based on areas of shielding thickness over 2000 points culculated by CATIA (3D CAD) software.

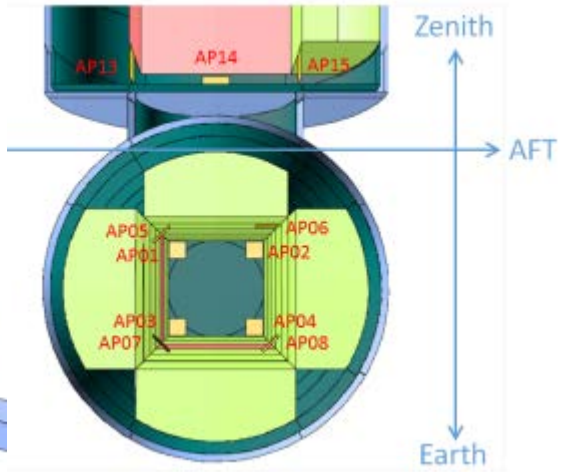
Benchmark study to evaluate the accuracy of the simulation analysis with :

- Dose results obtained from Area PADLES series experiment #1 to 10 in variation of solar activity (Absorbed doses, Dose equivalents, QF and LET distributions)



Shielding distribution from center of the KIBO





PHITS Shimulation flow chart

Date and Altitude of ISS

input

GCR proton and helium spectra and Solar modulation potential : Model used in EXPACS*
Geomagnetic transmission function: CREME96*** as functions of the altitude of ISS
Trapped proton spectra: AP-8 implemented in SPENVIS****
GCR heavy ion (Z>2) spectra: Badhwar and O'Neill model 2010**

output

Mean cosmic-ray spectra during the ISS KIBO experiment

PHITS Particle Transport Simulation with

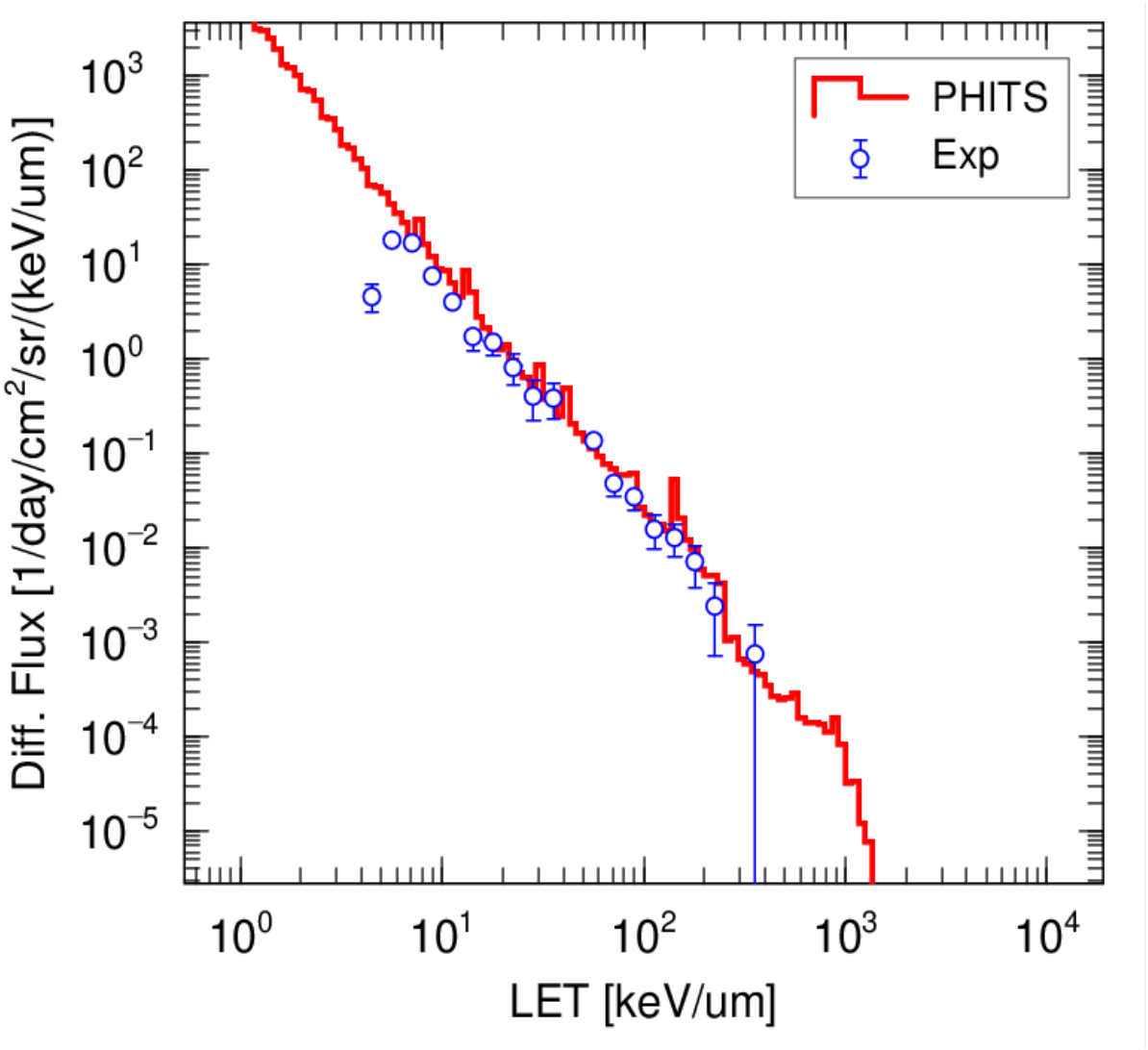
Virtual ISS KIBO

NUNDO Phantom

- Particle fluxes and heat inside the virtual Kibo module
- Doses, dose equivalents and LET distributions inside each organ of NUNDO

* T. Sato et al, Radiat. Res. 170, 244 (2008) or http://www.phits.jaea.go.jp/expacs/
** P.M. O'Neill, IEEE Trans. Nucl. Sci. 57, 3148 (2010)
*** https://creme.isde.vanderbilt.edu/
**** http://www.spenvis.oma.be/

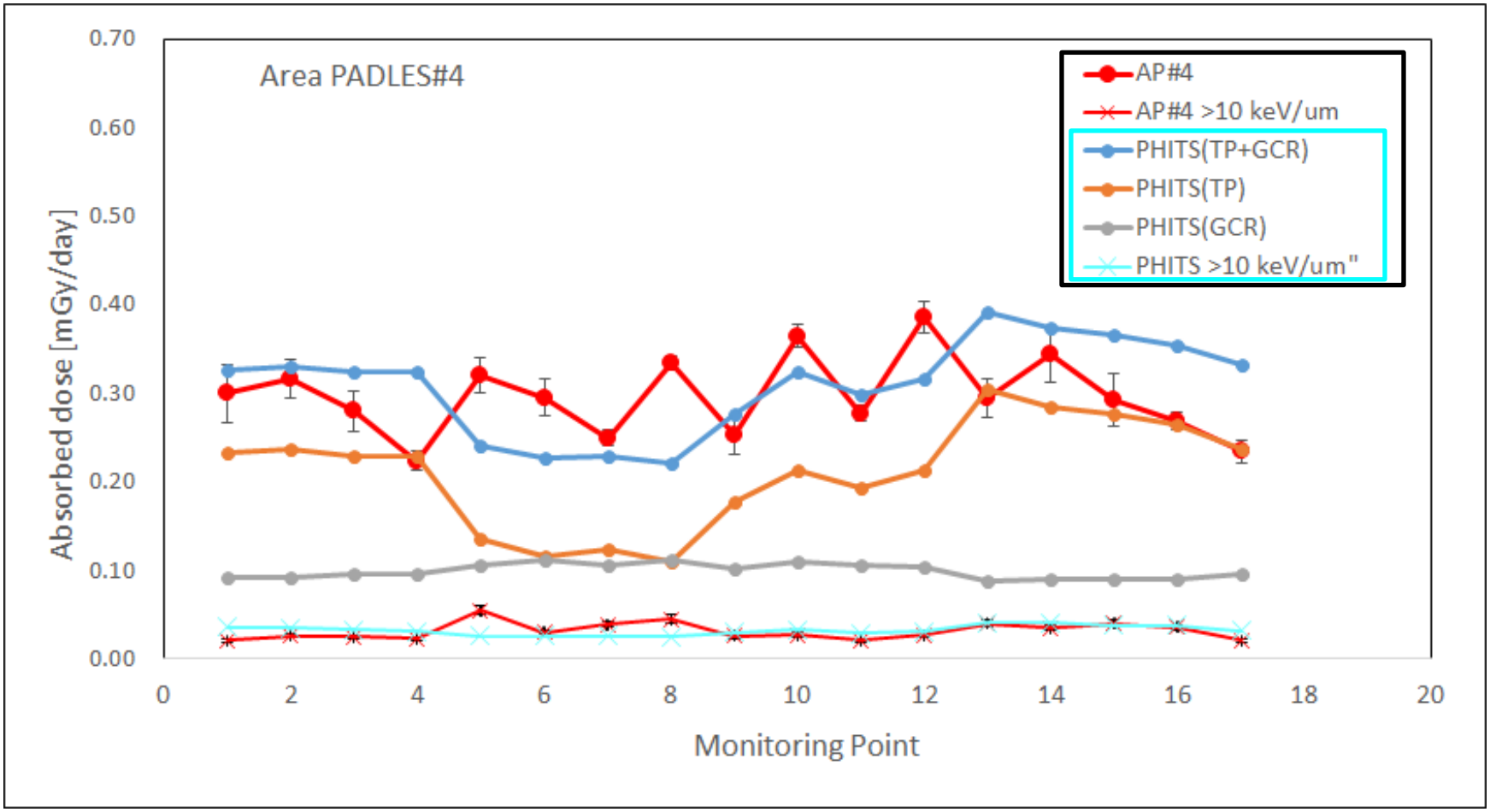
Area PALDES Benchmark evaluation between actual meas. and PHITS Cal.



The LET distributions (in monitoring point 1) measured in the Area PALDES #4 experiment are compared to results of PHITS calculations using a well developed shielding model of the KIBO.

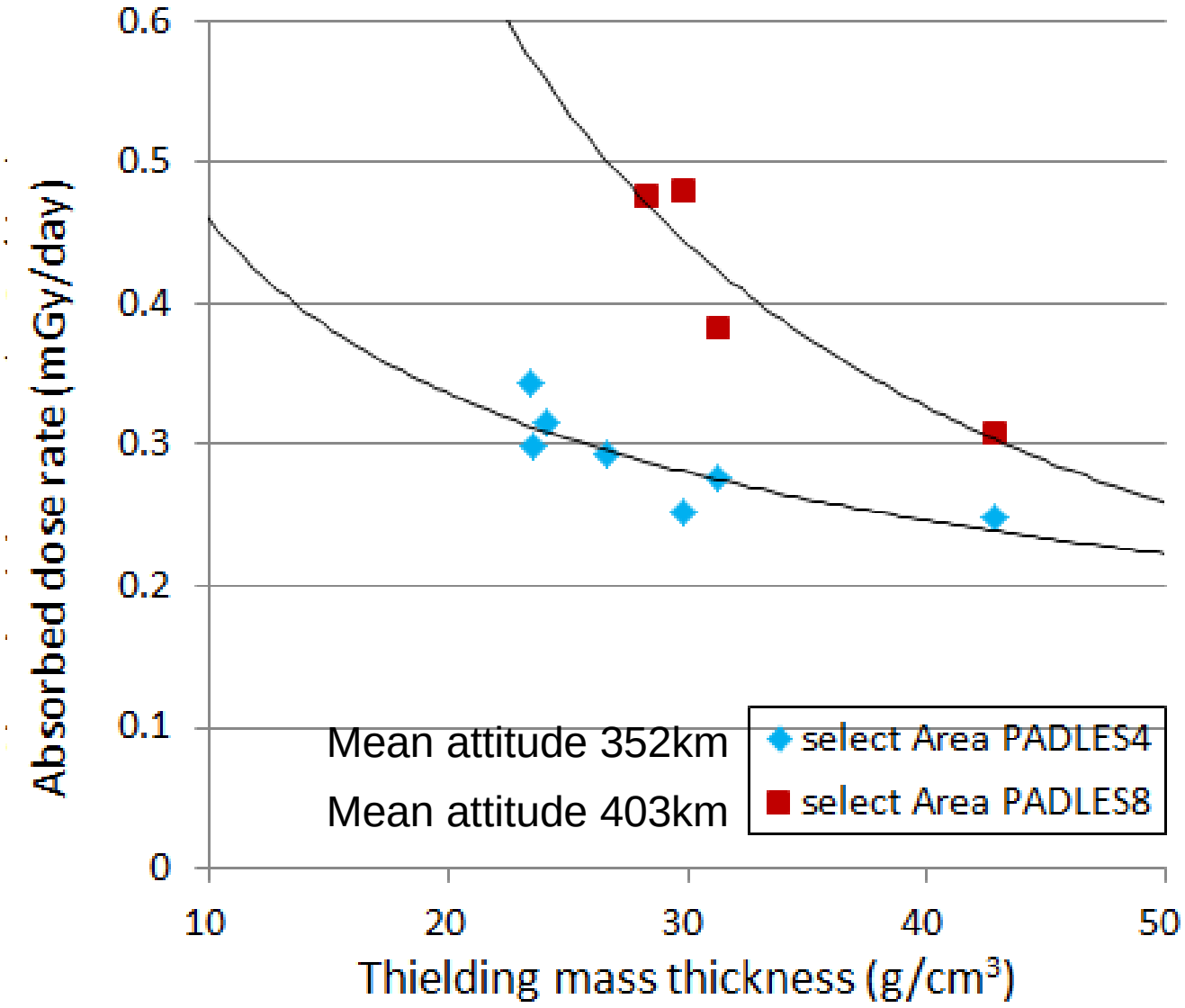
Area PALDES Benchmark evaluation between actual meas. and PHITS Cal.

Estimated shielding thickness changed (22.2 to 50.3 g/cm^2) depending on monitoring points, doses from GCR doesn't change. Fluctuation of doses from trapped protons conributes the total does fluctuations.



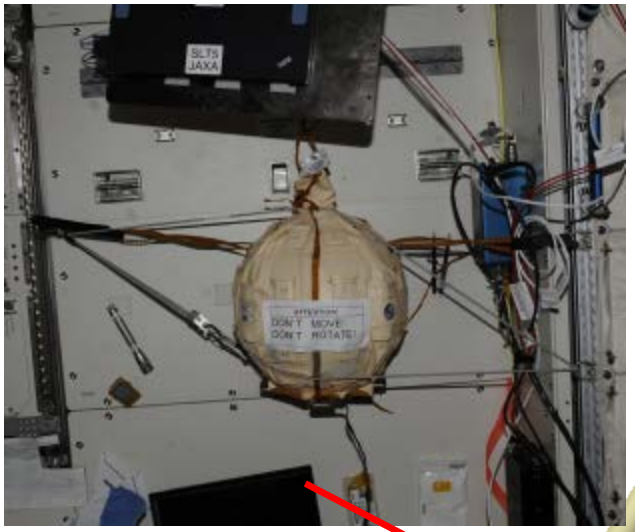
Comparison between Area PADLES#4 measurement and PHITS calculations in exact geometry of Kibo(ISS)

Area PALDES Correlation between actual meas. and thielding mass thickness with depending ISS attitude change



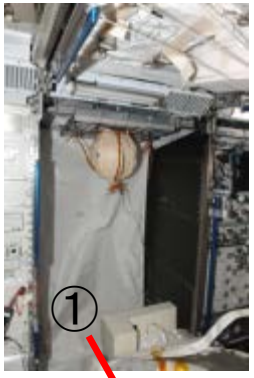
Thileding mas s thickness of 17 Area PADLES monitoring point sare in the 22.2 to 50.3 g/cm^2 range.

Two Matorshka Experiments were conducted abored the ISSS KIBO



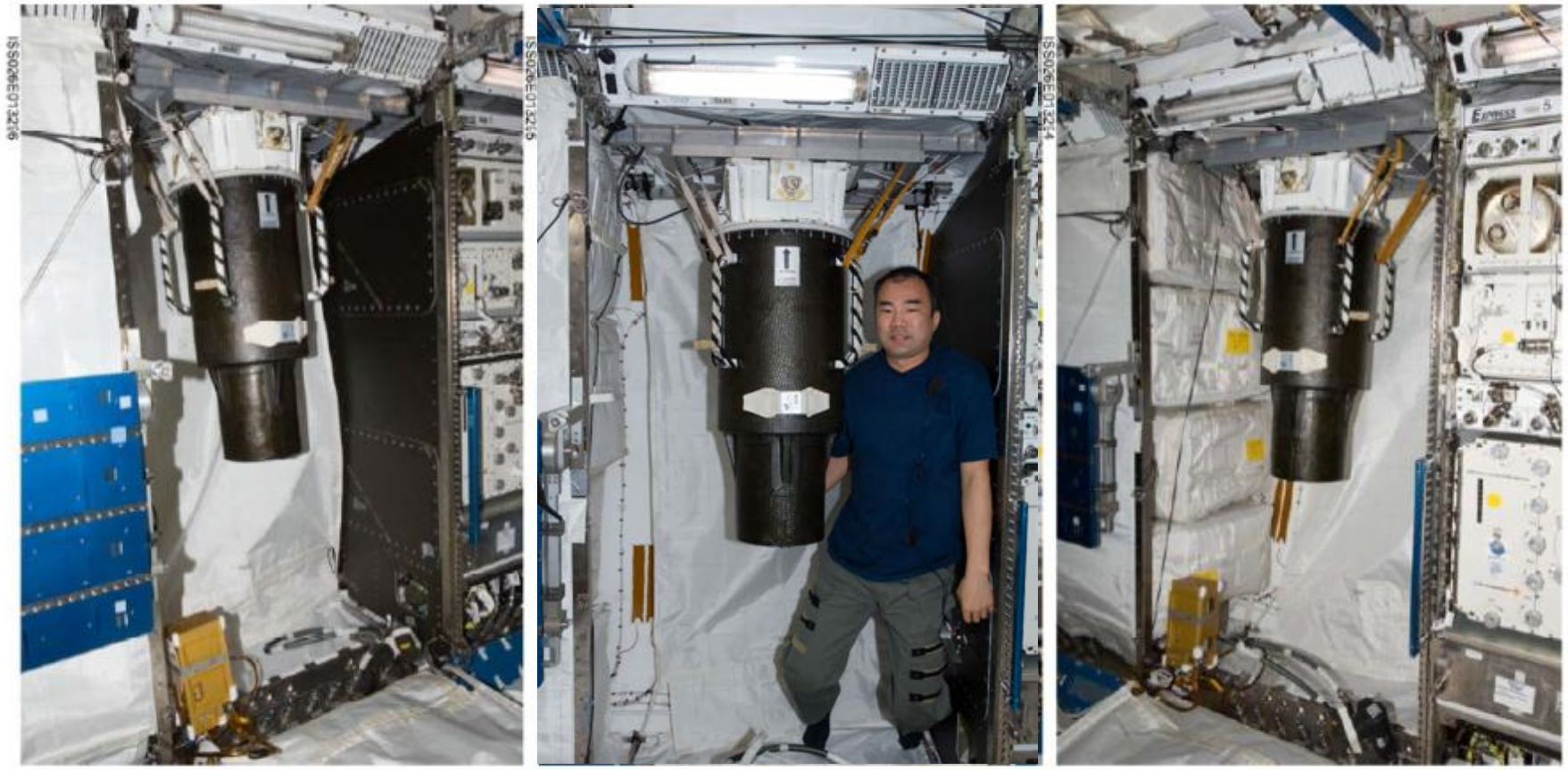
① ESA/DLR/ROSCOSMOS/JAXA
Matroshka 2B_KIBO

② ROSCOSMOS/IBMP Mat-R #1
experiment onboard the KIBO.



③ ROSCOSMOS/IBMP Mat-R #2
experiment onboard the KIBO.

① Space Radiation Dosimetry using PADLES in the ISS Japanese Experiment Module Kibo

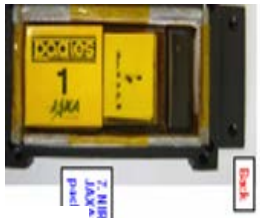


MATROSHKA in KIBO: May 2010 – March 2011

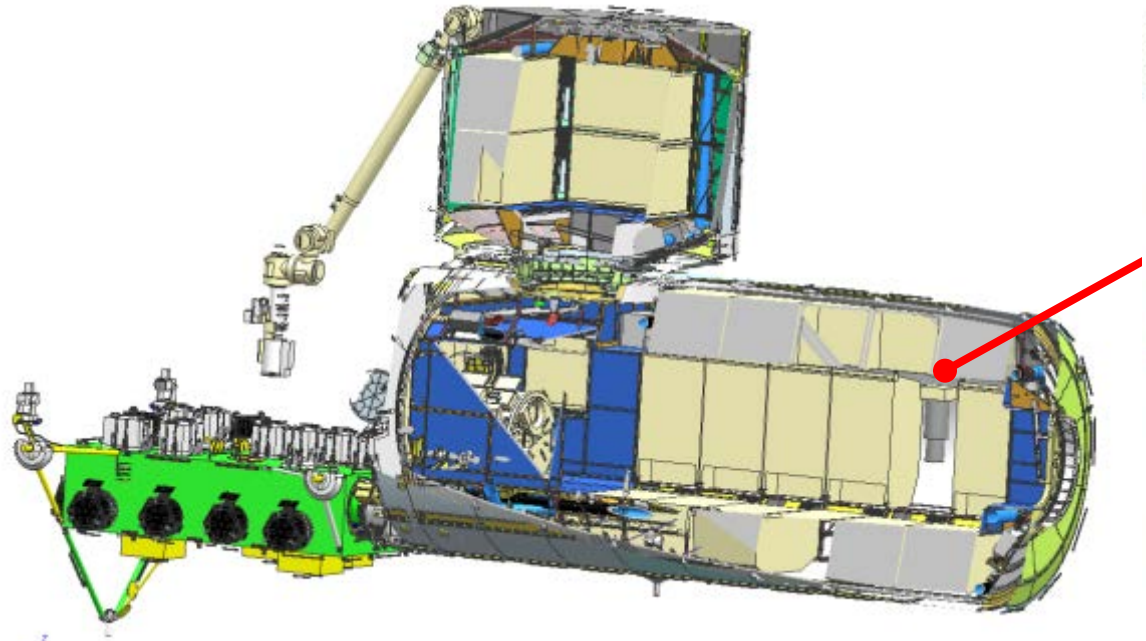
Matroshka 2B_KIBO Flight conditions (Apr. 2010 to Mar 2011)

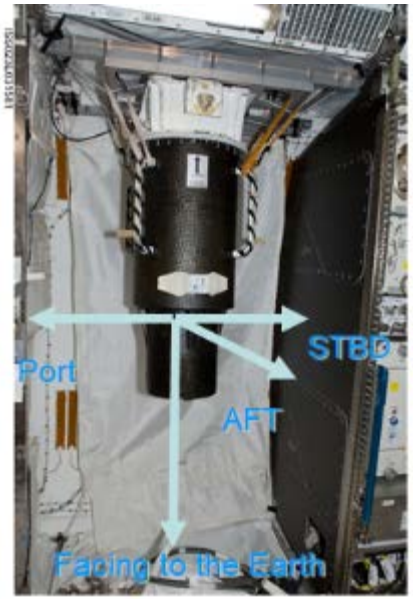
The MATROSHKA project is a series of experiments using an anthropomorphic upper torso phantom for assessing the risk to astronauts from radiation exposure inside and outside the ISS. The phantom equipped with various type of active and passive dosimeters to measure depth doses in organ locations (skin, eye, lung, stomach, kidney, intestine and top of the head).

Event	data	Vehicle	days
Launch	29 Apr. 2010	37P Progress	Total: 322 Phantom:311
Installation	4 May 2010		
De-installation	11 Mar 2011		
Return	17 Mar 2011	24S	

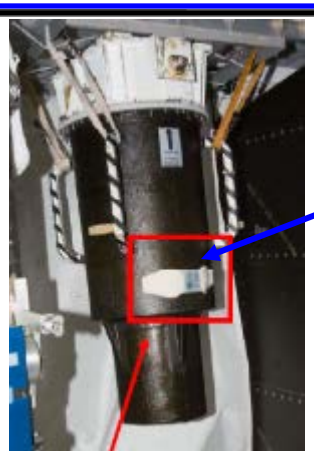


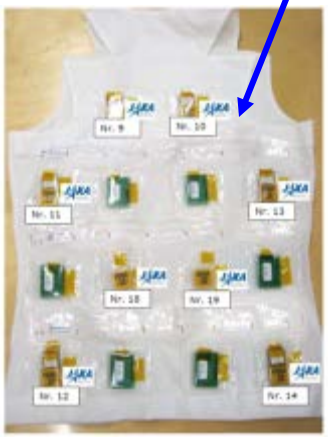
PADLES





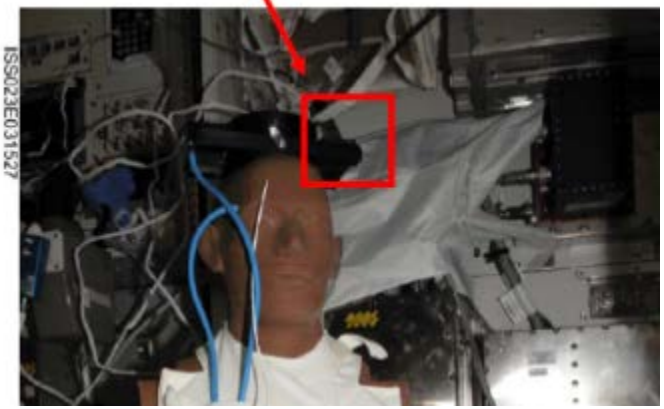
19 PADLES Positions on and inside the anthropomorphic phantom

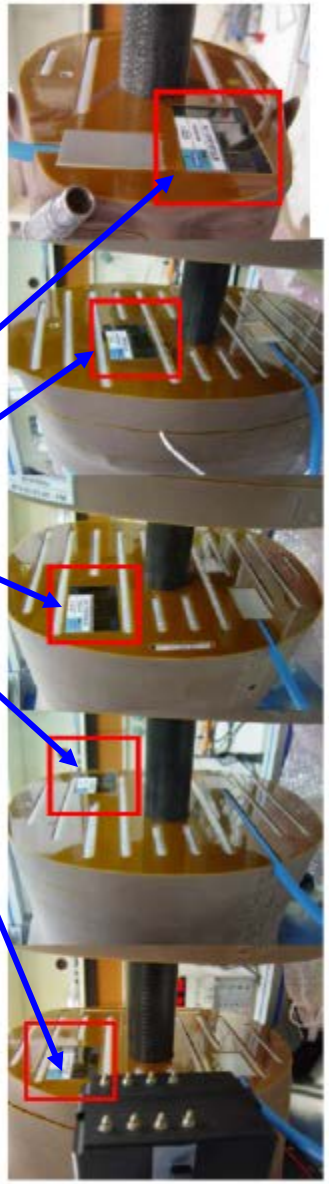




	Organs	Number
Outer container	Reference 1	1
	Reference 2	1
Poncho Front	Skin	3
Back	Skin	8
NPTD	Eye	1
	Lung	1
	Stomach	1
	Kidney	1
	Intestine	1
	Top of the Head	1

JAXA PADLES # 20 - #25: Background Detector Packages at DLR, Cologne, German



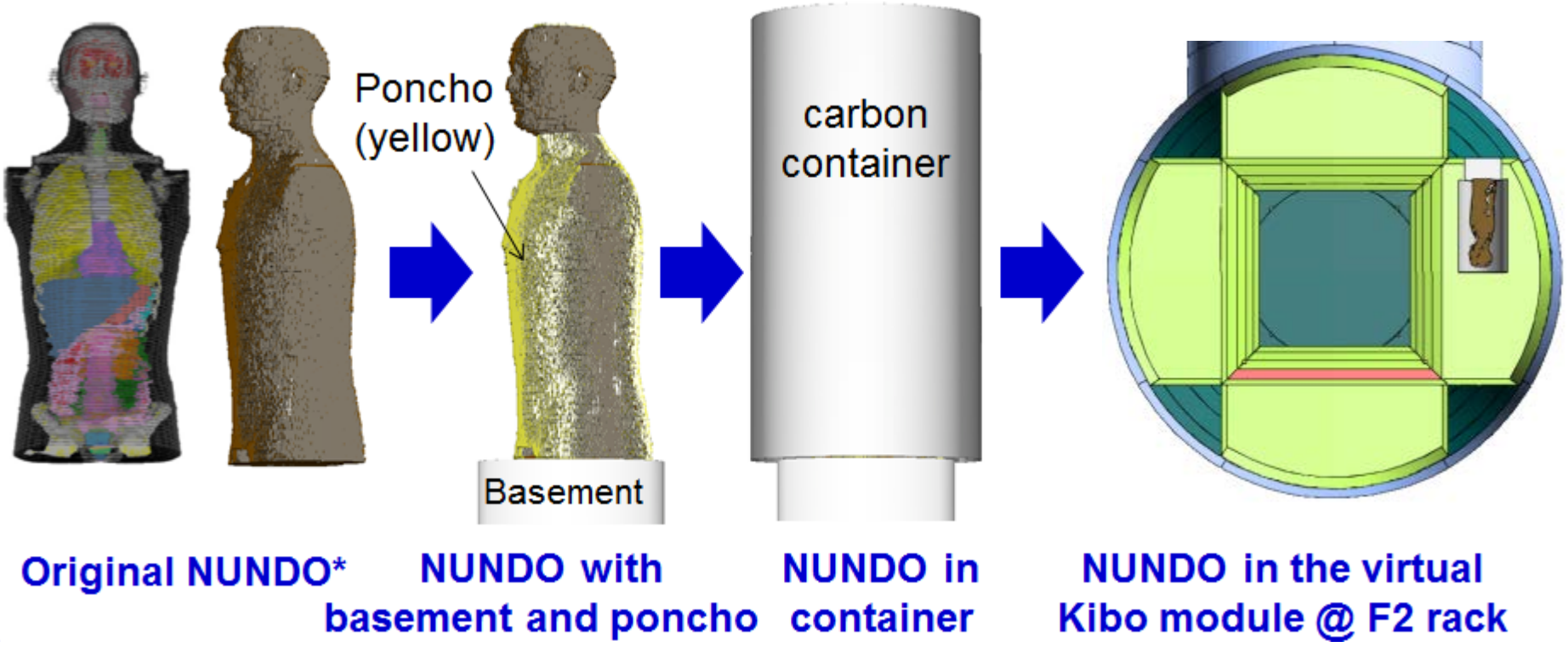


Incorporation with NUNDO Phantom into Virtual ISS KIBO (Averaged thickness is 26.5 g/cm^2)

What is NUNDO phantom?

- Constructed based on the CT-image of the RANDO phantom
- Segmented into various organs and tissues

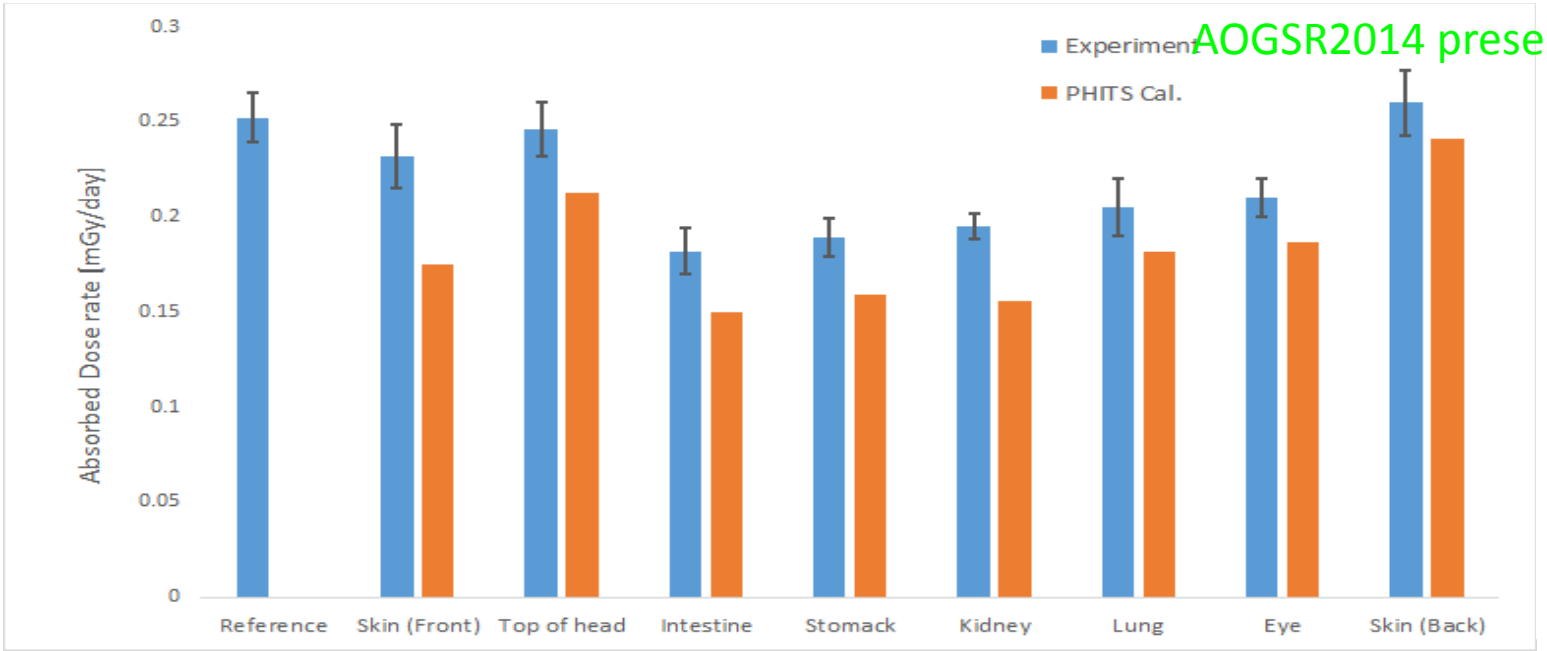
voxel-based NUmerical human model of RANDO phantom

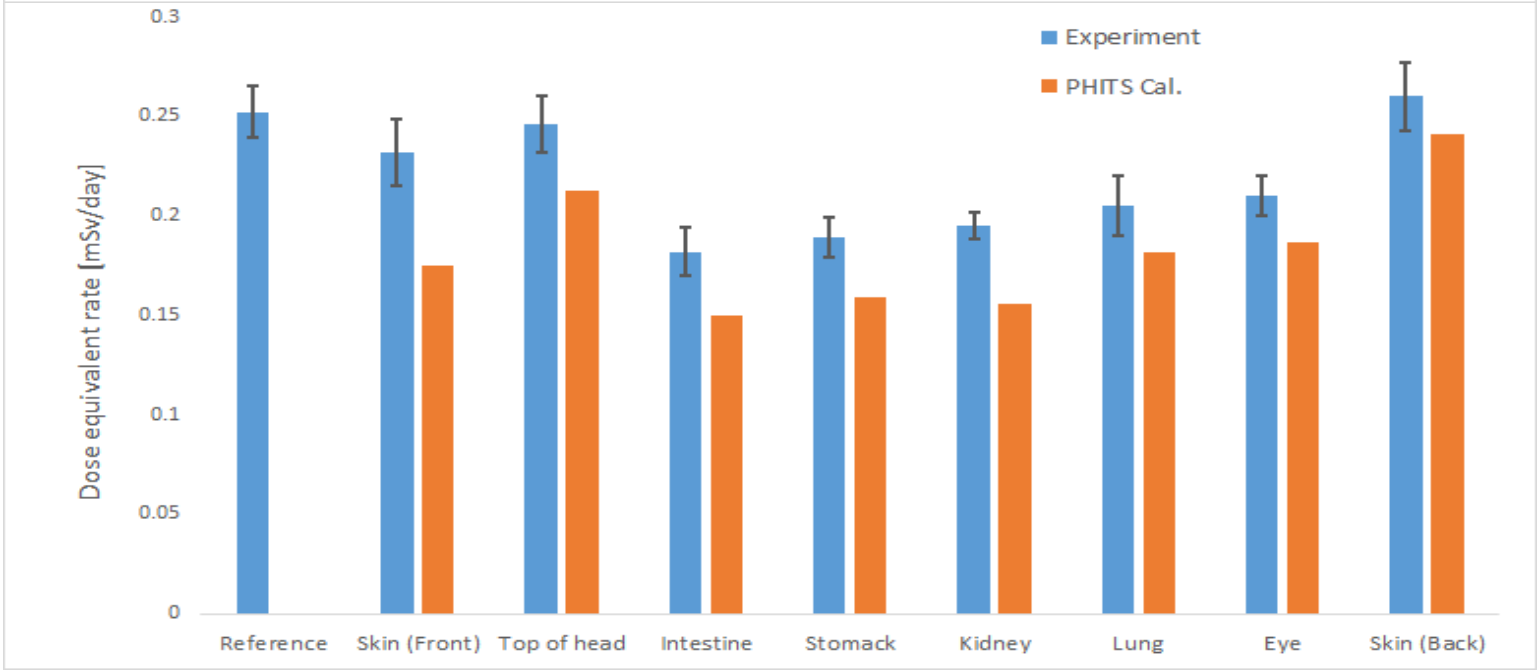


Tatsuhiko Sato[1*], Aiko Nagamatsu[2], Kazuo Takeda[3], Koji Niita[3], Monika Puchalska[4,5],Lembit Sihver[4] and Guenther Reitz[6],
Astronaut Dose Estimation Using the PHITS Code in Combination with Realistic Models of the Kibo Module and the MATROSHKA Phantom, Heavy Ions in Therapy and Space Radiation Symposium 2013, Chiba, May 15-18, 2013

Matroshka_KIBO Benchmark evaluation between actual meas. and PHITS Cal.

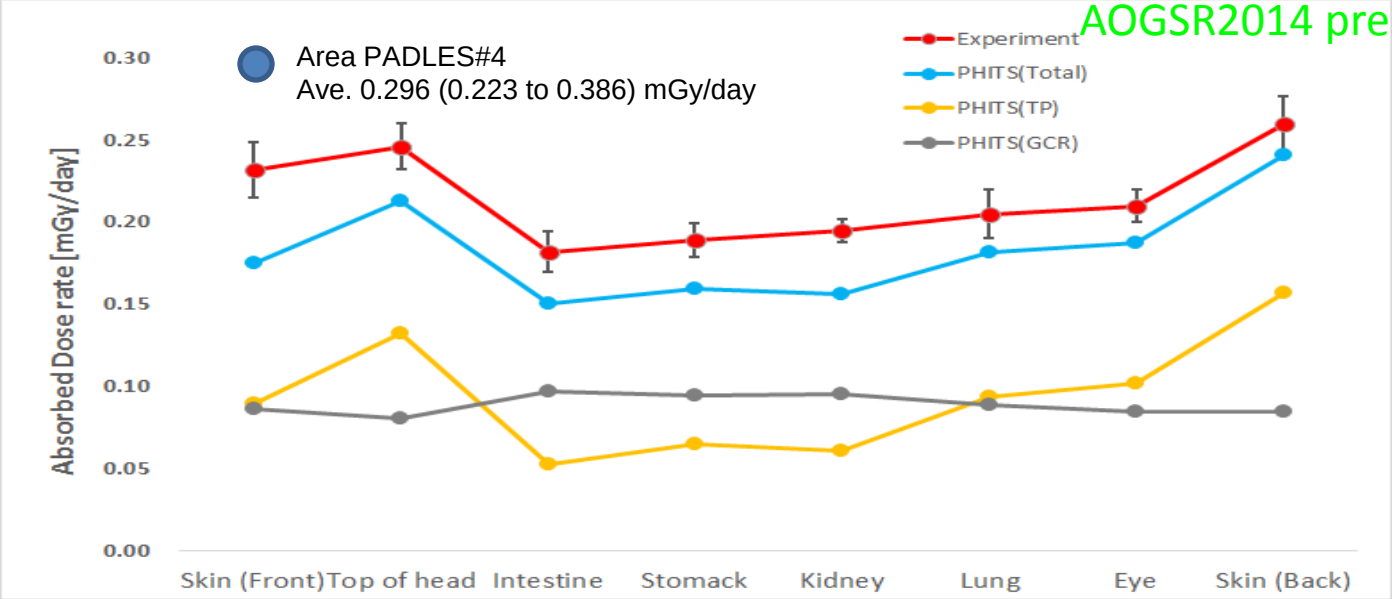
AOGSR2014 presentation

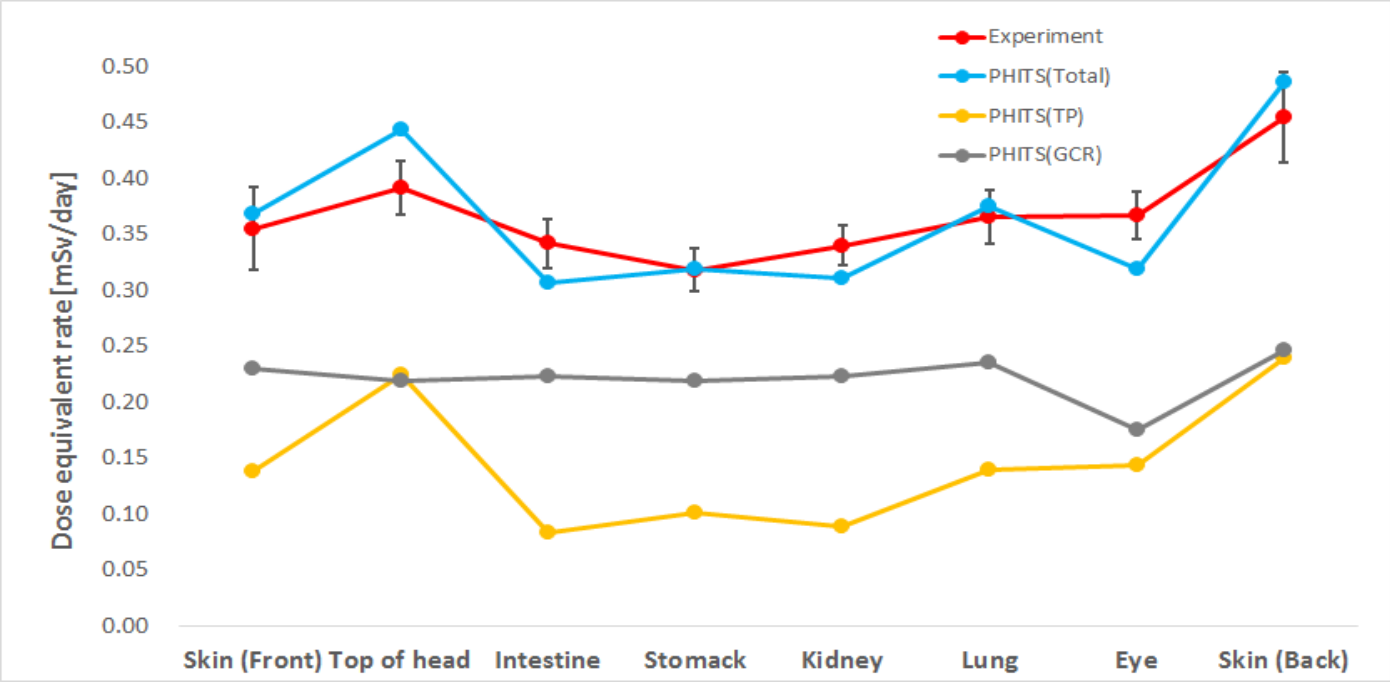




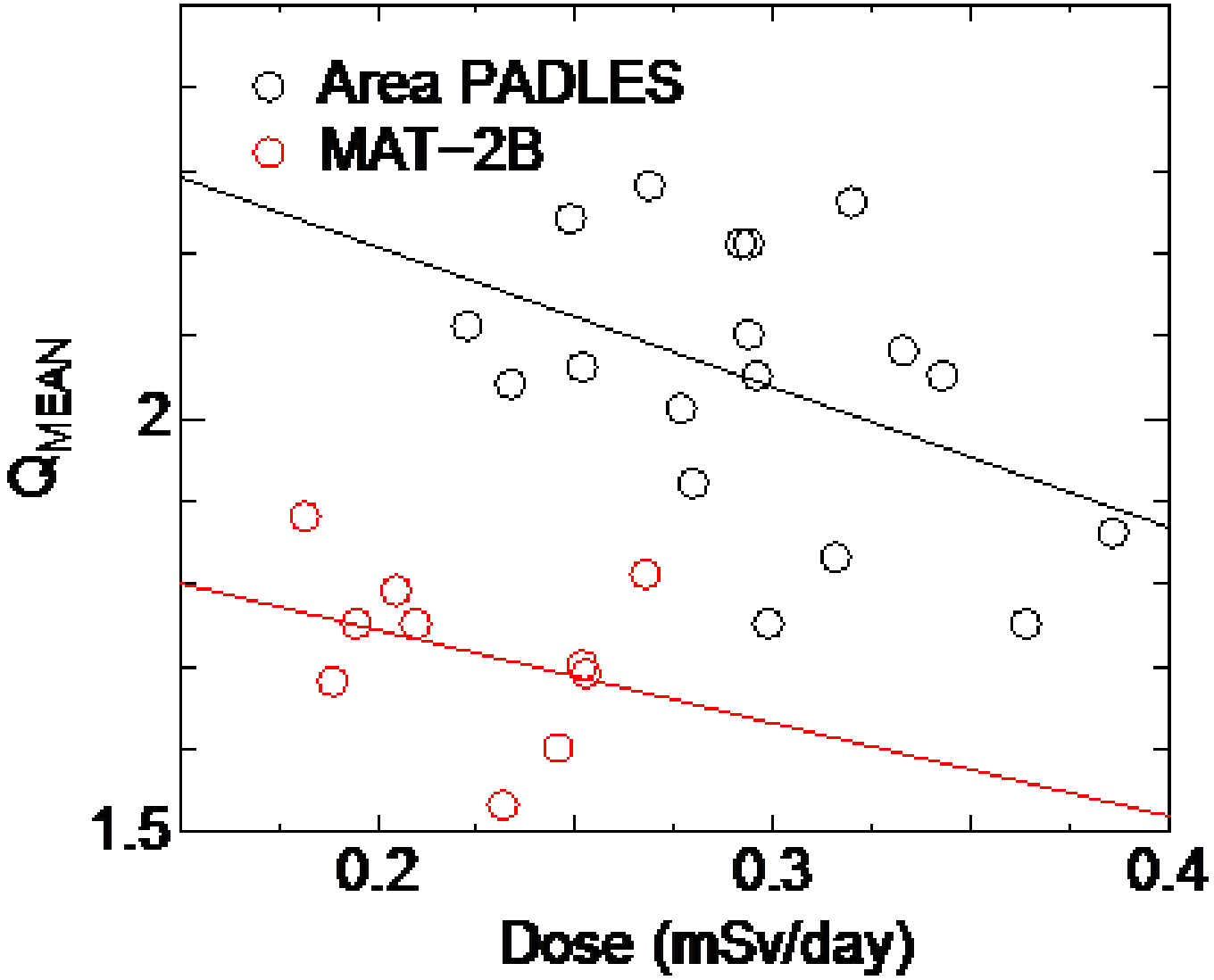
Matroshka 2B_KIBO evaluation with PHITS Cal.

AOGSR2014 presentation

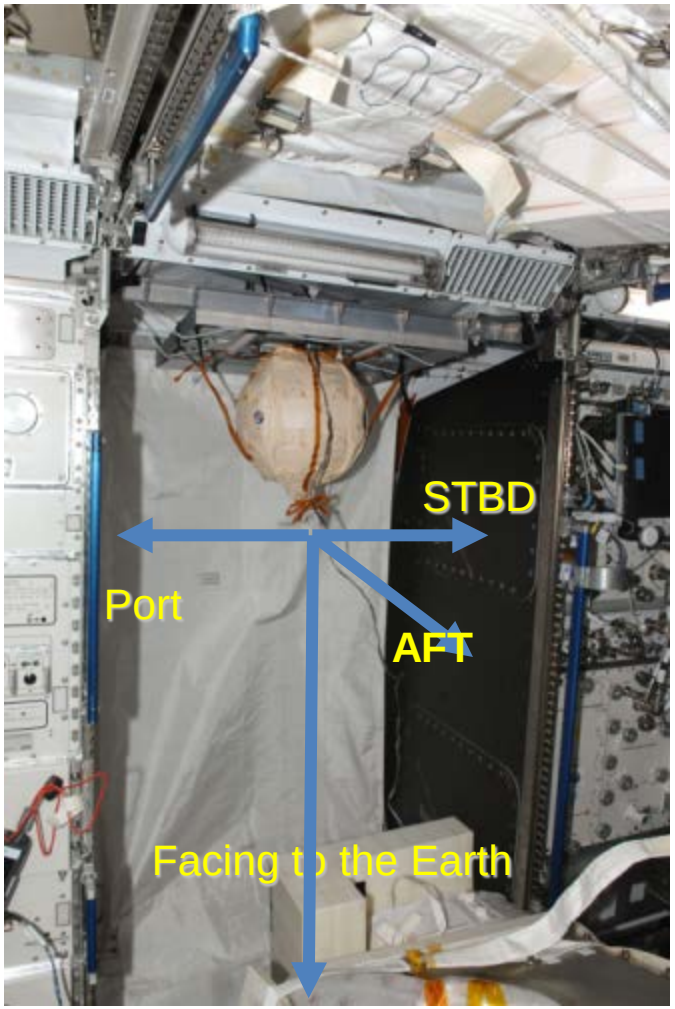


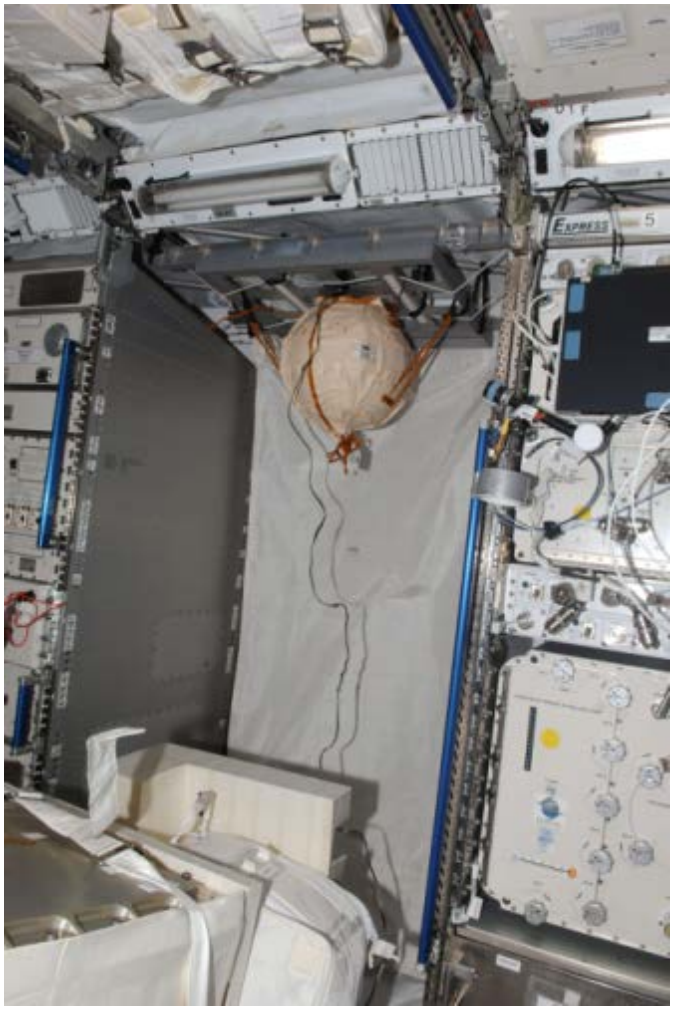


Correlation between between measured absorved doses and Q_{MEAN}



② Space Radiation Dosimetry using PADLES in the ISS Japanese Experiment Module Kibo

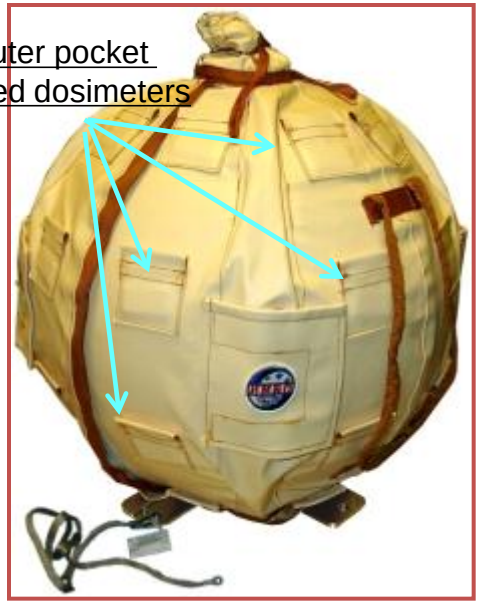


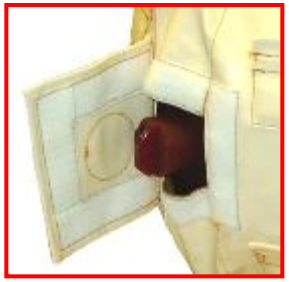


Matroshka-R Experiment #1 (14 May - 16 Sep. 2012 for 125 days)

■ Verification of dose distribution in a human body in space flight using very simplified model of spherical tissue equivalent phantom

- Long-term dose measurements inside the phantoms, in the various habitat modules
- Verification of the space radiation transport codes for calculating the dose distribution inside ISS and inside the phantom





Rod contained dosimeters

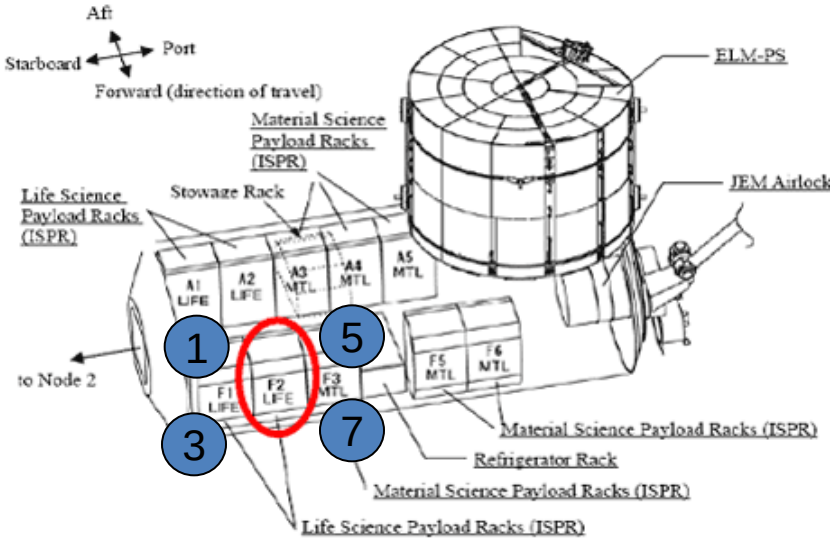
Size: 370 x 370 x 390 mm; mass: 32 kg

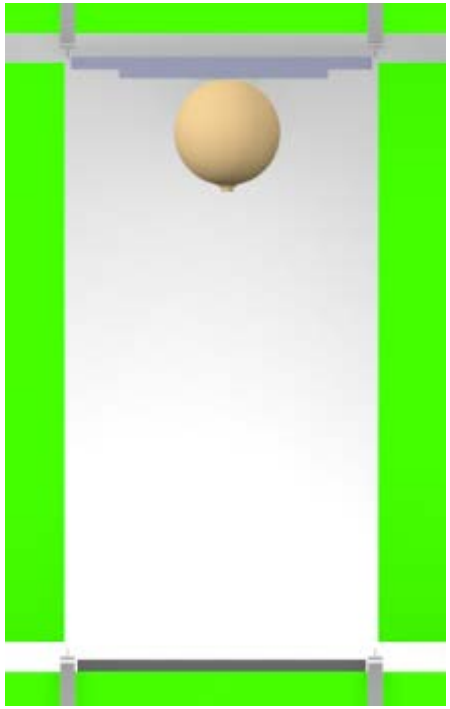
Shurshakov et al., 2008; Jadrnickova et al., 2010; Ambrozova et al., 2011 and Kolskova et al., 2012

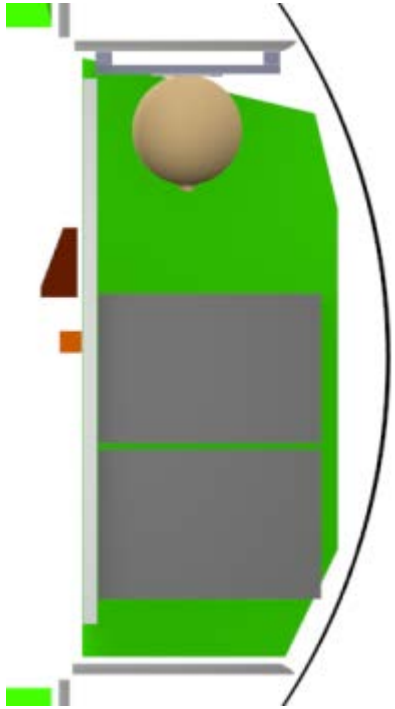
Experimental conditions of Matorshka-R experiment #1 (Inc31/32)

Event	Data	Vehicle	Location/Days
Launch	15 May. 2012	30S Soyuz TMA-04M	KIBO: JPM1F2 Rack2 Total: 125 (in Phantom) :114 Between 23 and 24th over solar minimum.
Installation	21 May 2012	GMT142	
De-installation	12 Sep 2012	GMT256	
Return	15 Sep 2012	30S Soyuz TMA-04M	

*Base of the Spherical phantom was attached to the zenith of Rack 2 with the knot facing to the Earth.



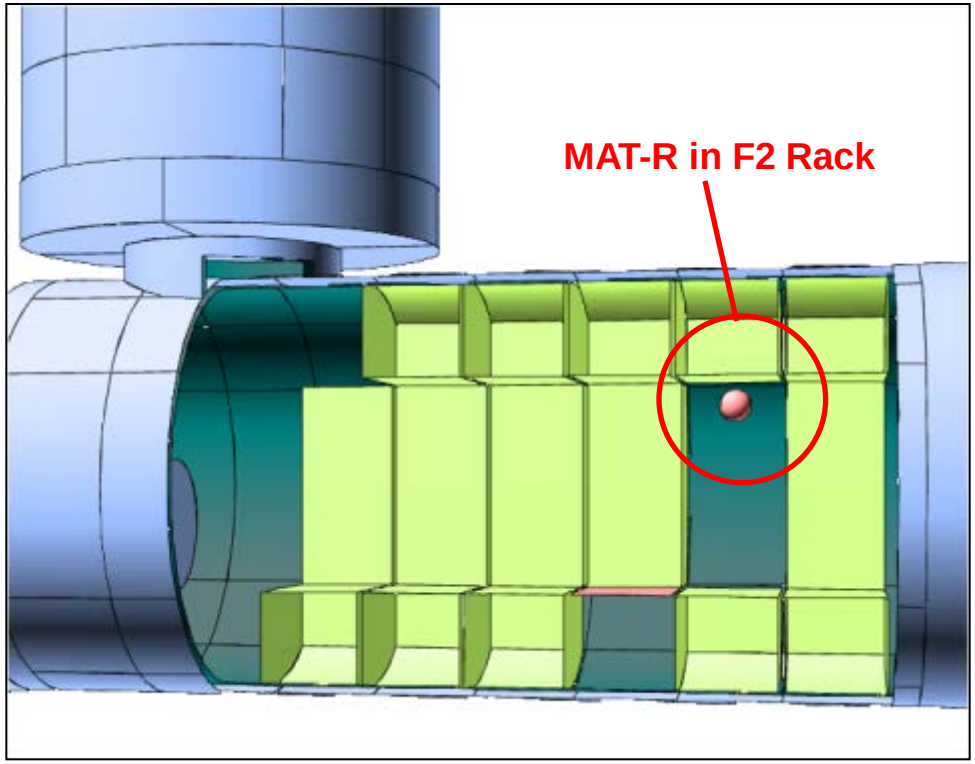


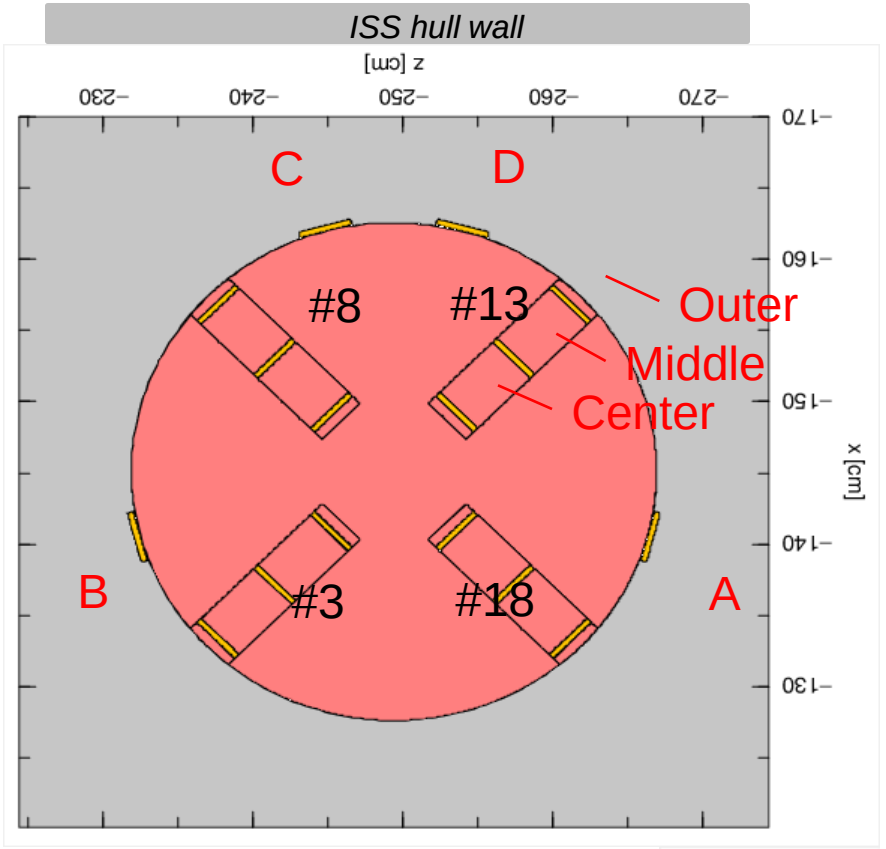


Area PADLES near the phantom

Incorporation with Matroshka-R Phantom into Virtual ISS KIBO (Averaged thickness is 26.5 g/cm^2)

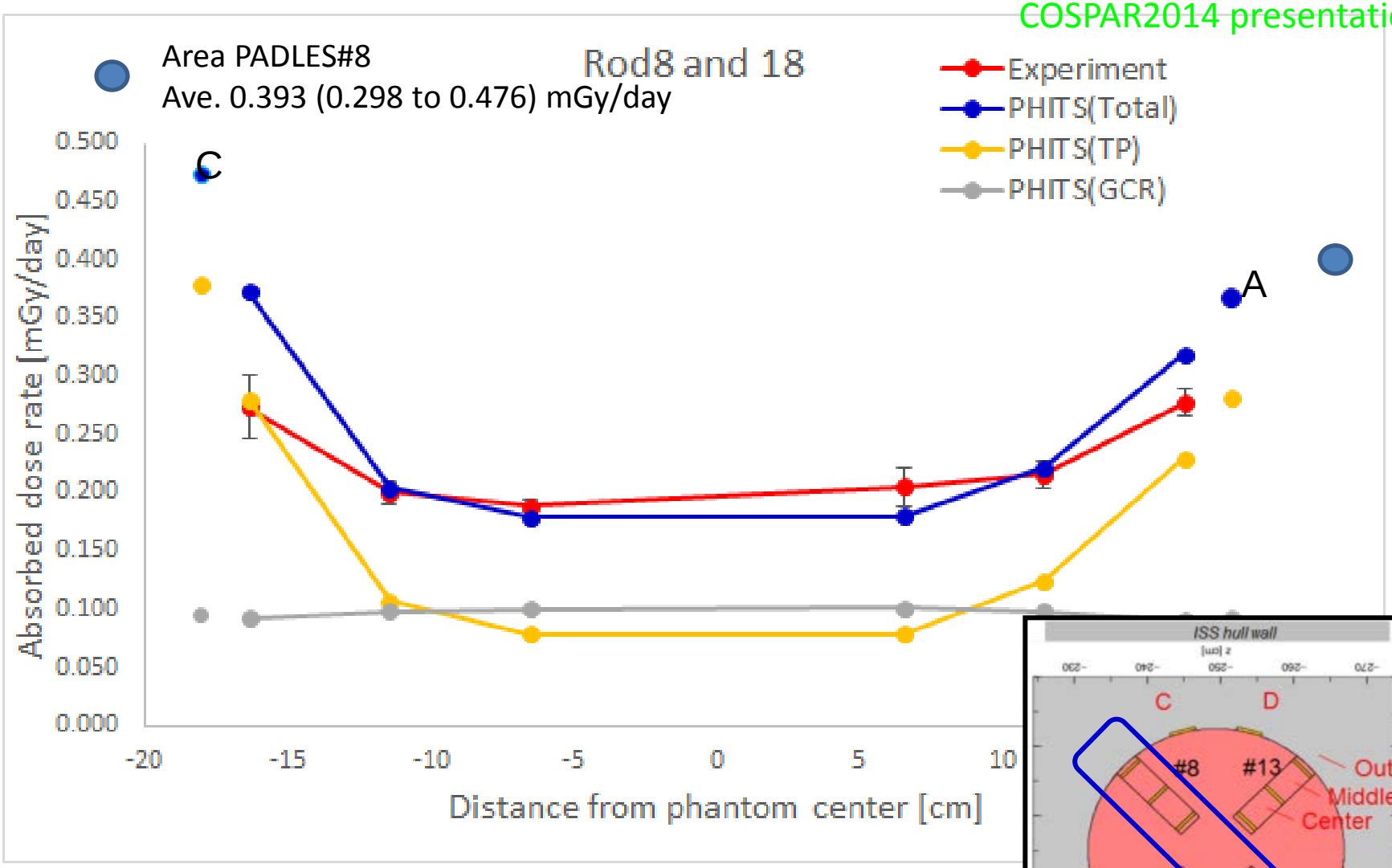
We estimated simulated doses of following 16 points.
- A - D in phantom surface : 4 points
- Outer, Middle, Center in each rod : 12 points in total





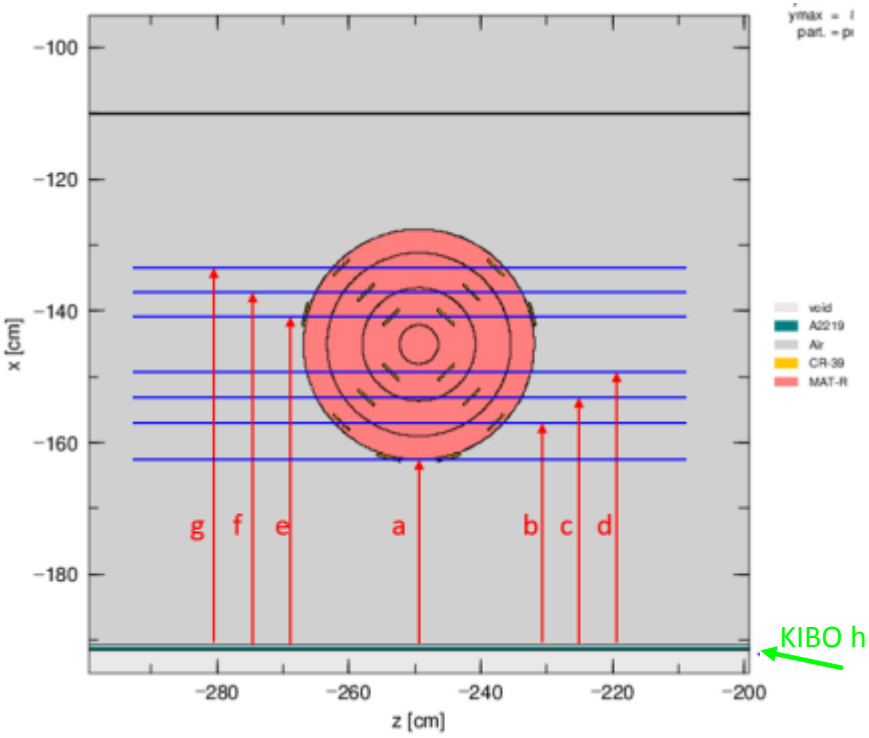
Absorbed doses: Matroshka_R evaluation with PHITS Cal

COSPAR2014 presentation

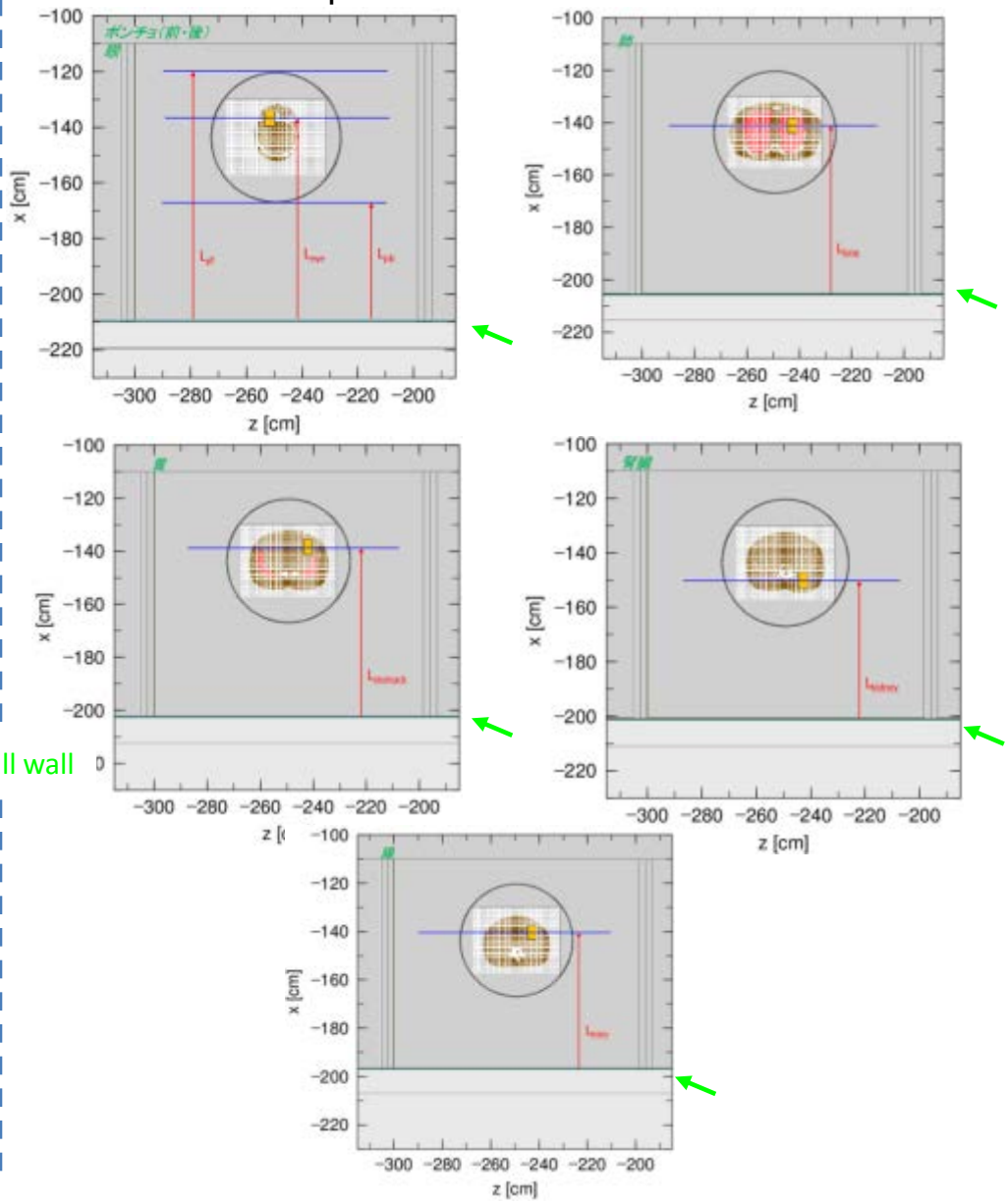


Pleliminary attemp: Distance from ISS KIBO Hull to maeasurement point in both Matroshka experiment

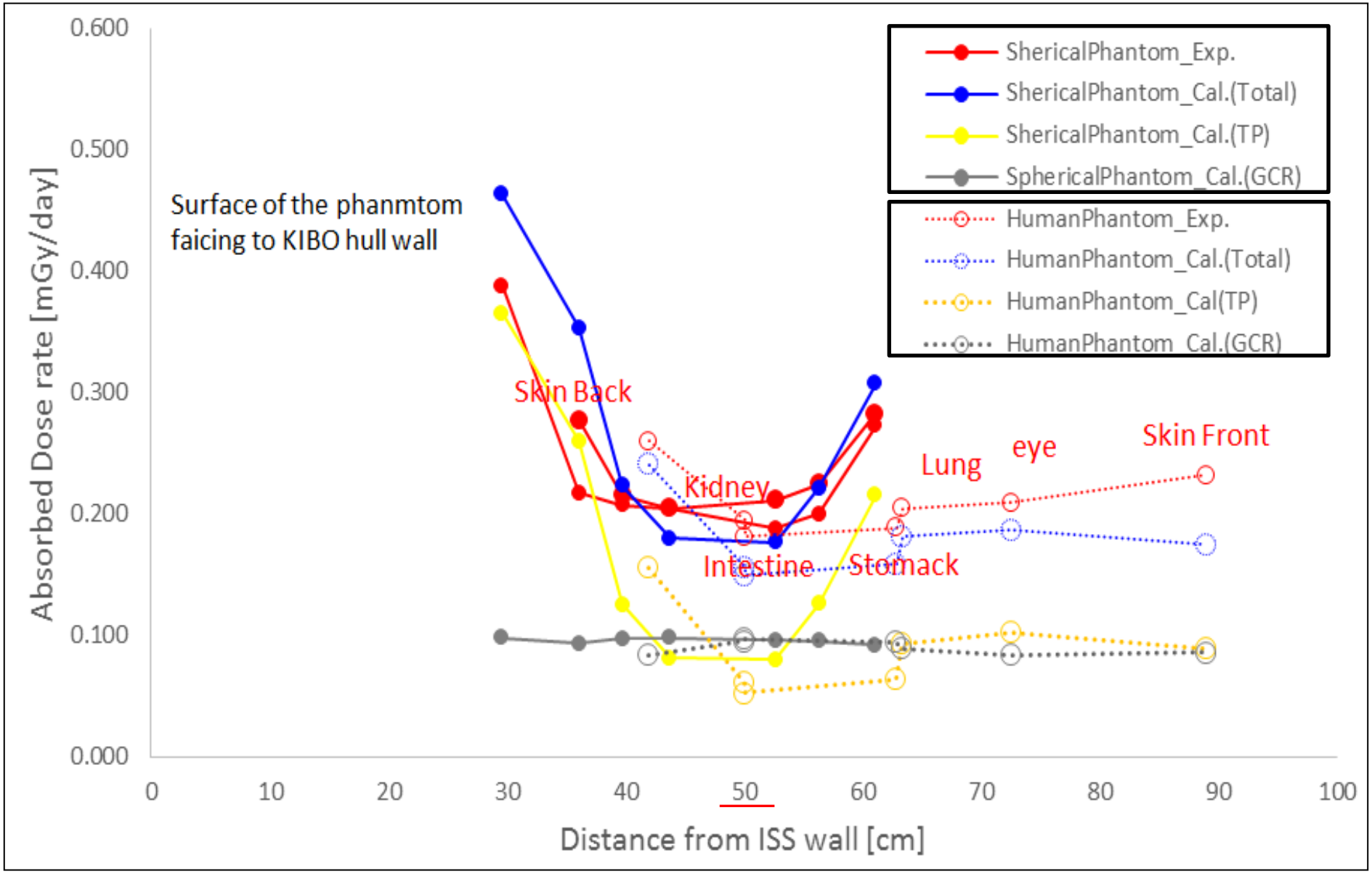
① ESA/DLR/ROSCOSMOS/JAXA
Matroshka 2B_KIBO



② ROSCOSMOS/IBMP Mat-R #1
experiment onboard the KIBO.



Pleliminary attemp Correlation between between Absorved doses and distance from hull



Summary 1

Benchmark study to evaluate the accuracy of the simulation analysis between actual measurement onboard the ISS KIBO and PHITS calculation with:

- Dose results obtained from Area PADLES series experiment #1 to 10 in the beggining of 23th to the maximum of the 24th solar cycle
- Matroshka-2B KIBO Anthropomorphic Phantom
- Matroshka-R Sperical phantom

- Doses of Experiment were very close to the doses from PHITS cal.

- Experiment and PHITS cal. : ISS hull wall > ISS interier
  ⇒ The doses close to Kibo hull walls were higher than inside the Kibo.

- TPs doses decrease with increasing shielding thickness.

- The differences of proximity to the hull wall weren't related to change of LET distributions.
  ⇒ GCR component didn't change the stopping power, considering the differences of ISS KIBO hull wall thickness.

Summary 2

■ TP and GCR

We estimated the doses using the PHITS simulation corpolated virtual KIBO.
The change in doses appeared to be due mostly to trapped protons because doses from GCR didn't change depending on the doseter location from the hull and the two different ISS attitudes.

■ two phantoms shapes

The shape of the two phantoms are different:

- one is spherical and the other is anthropomorphic.

The Sperical phantom experiment was conducted at a lower attitude (352km) and the anthropomorphic experiments at a higher attitude (403km). Although doses at the higher attitude were expected to be higher, the results obtained for both experiments are identical for the phantoms at a distance of 50 cm from the hull.

Configuration and the different forms may have contributed to the difference in the doses. The current data involves distance from ISS wall plotted against absorbed dose rate; we are converting the current data from distance to thielding mass thickness to be plotted against the absobed dose rate to clarify the depth of absorption. We will try to present the finding in a subsequent presentation.