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

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WRMISS-23, Fukui, Sep. 4-6, 2018

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- Development of WASAVIES
  - ✓ Calculation procedure
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- Development of WASAVIES-EO
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Background

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)

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

- Solar energetic particle (SEP)

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

Download GOES proton flux & several NM count rates by every 5 min

↓

Check the occurrence of Ground Level Enhancement (GLE)

↓ Yes

Determine 4 parameters that characterize the event profile

↓

Nowcast & forecast the radiation doses in the atmosphere

WArning System for AVIation Exposure to SEP (WASAVIES)

TLE data

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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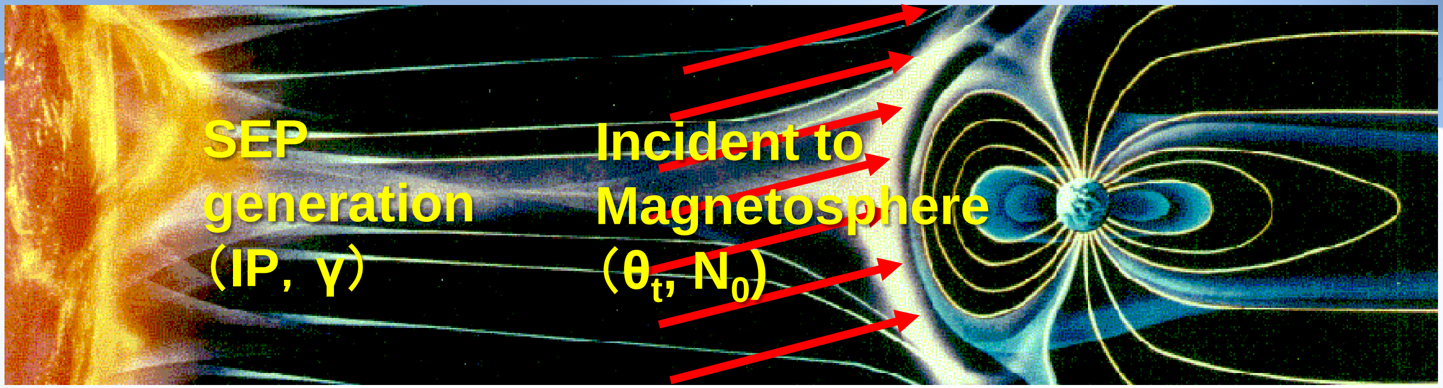
How to Estimate SEP Dose?



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

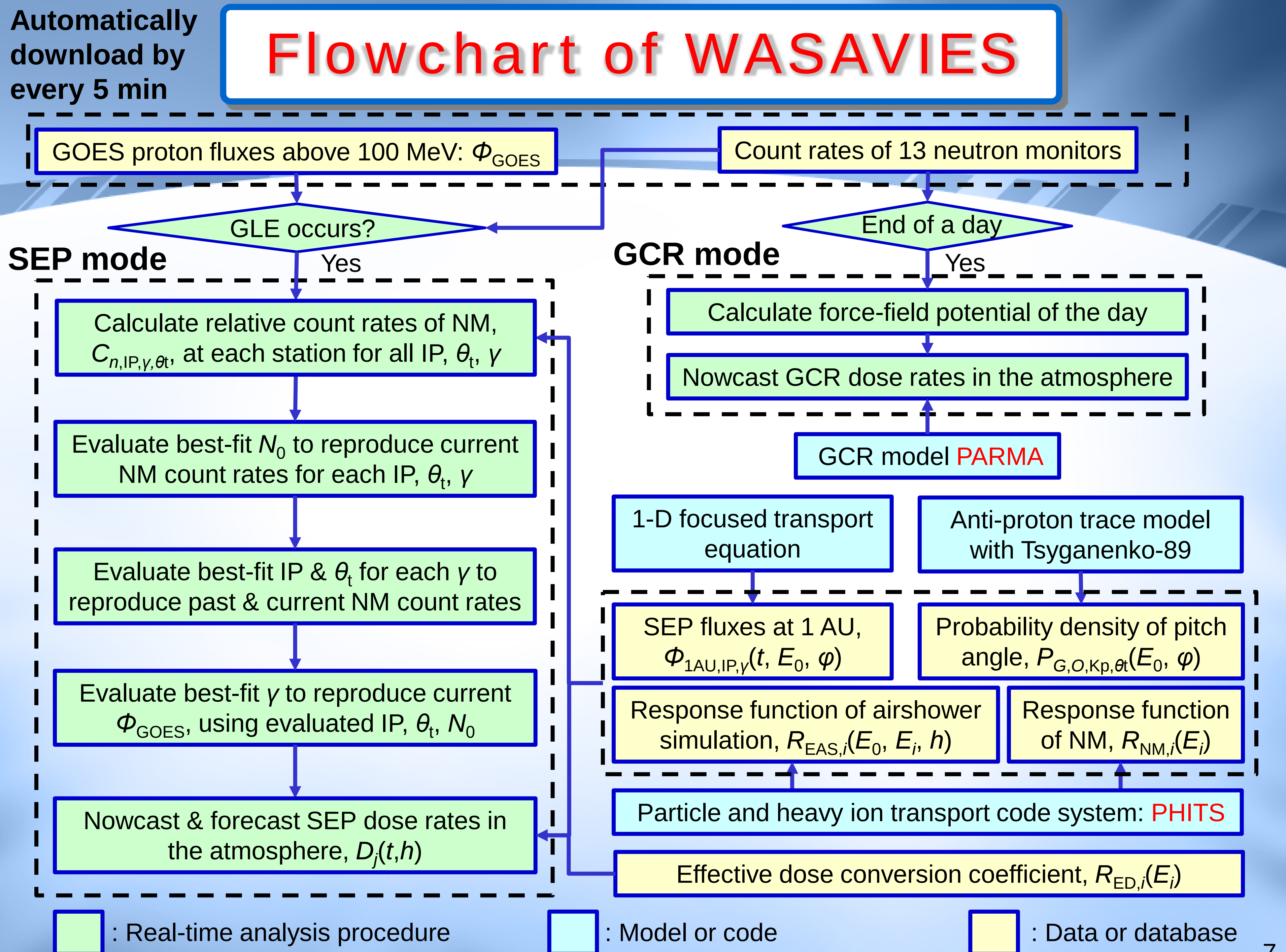
WASAVIES

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



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Event Selection

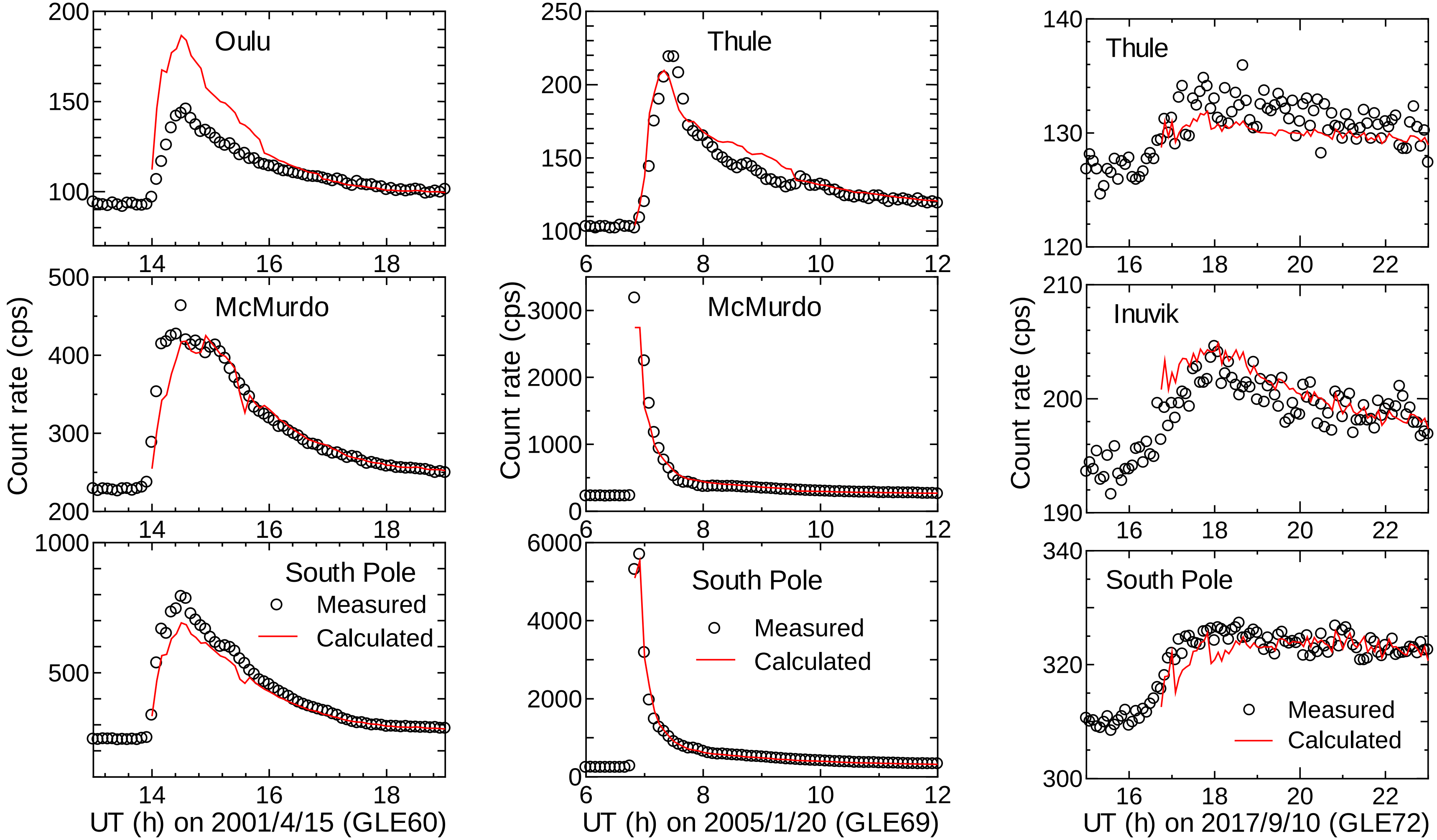
For reliable benchmark of SEP model ...

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

Profiles of analyzed events

	GLE60	GLE69	GLE70	GLE71	GLE72
Flare class	X14.4	X7.1	X3.4	X5.1	X8.2
Date, Year	Apr 15, 2001	Jan 20, 2005	Dec 13, 2006	May 17, 2012	Sep 10, 2017
Maximum NM increase rate	~200%	~2000%	~90%	~15%	~15%
Anti-isotoropy	No	Yes	No	No	No

NM Count Rates

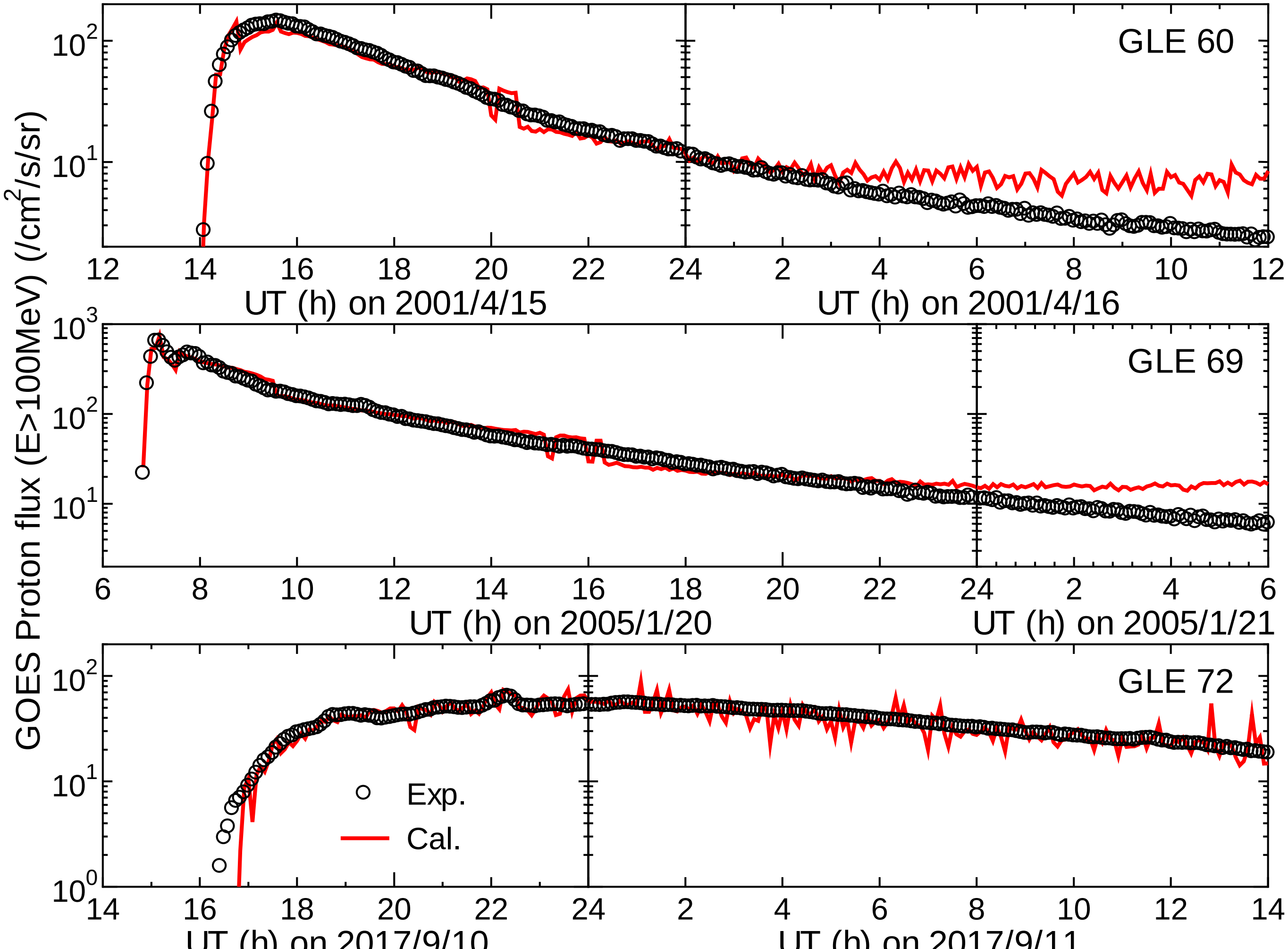


Comparison between measured and calculated count rates of some NM stations

Good agreement!!

Measured data taken from NMDB
(http://www.nmdb.eu/)

GOES proton flux (E>100MeV)

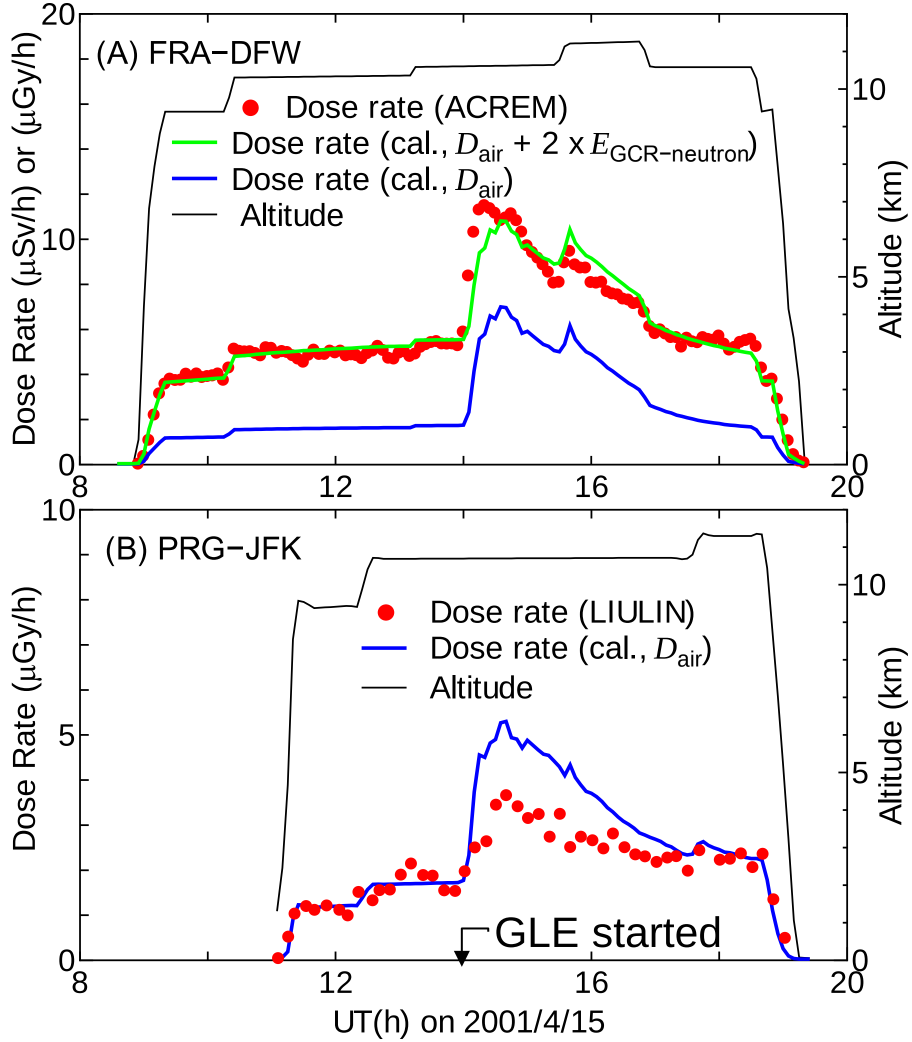


Comparison between measured and calculated GOES proton fluxes (E>100MeV)

Good agreement !!

Measured data taken from NOAA
(ftp://ftp.swpc.noaa.gov/pub/lists/particle/)

Validation with Flight-Dose Measurements



Bartlett et al. (2002)

Spurny and Dachev (2002)

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

WASAVIES can reproduce the experimental data very well!

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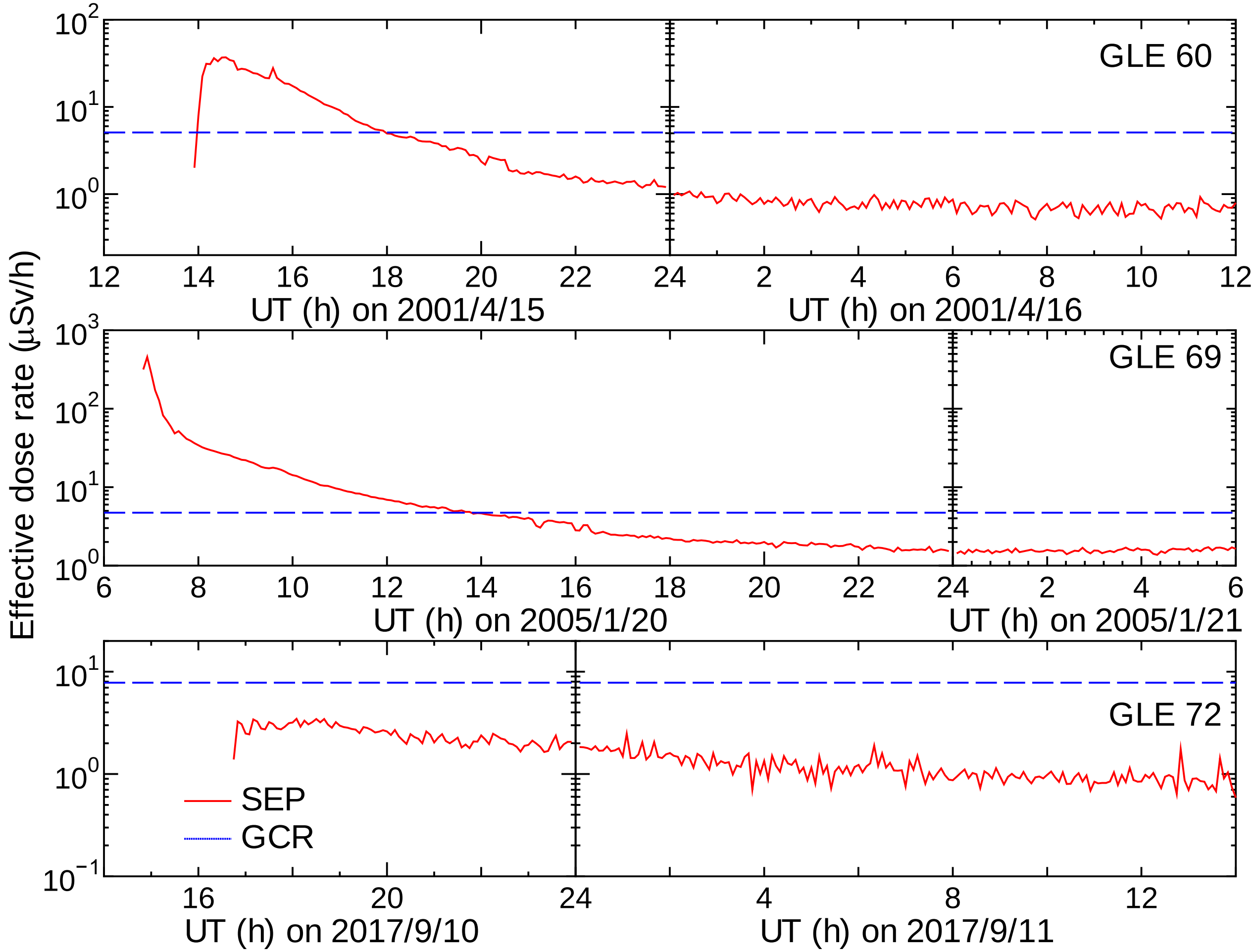
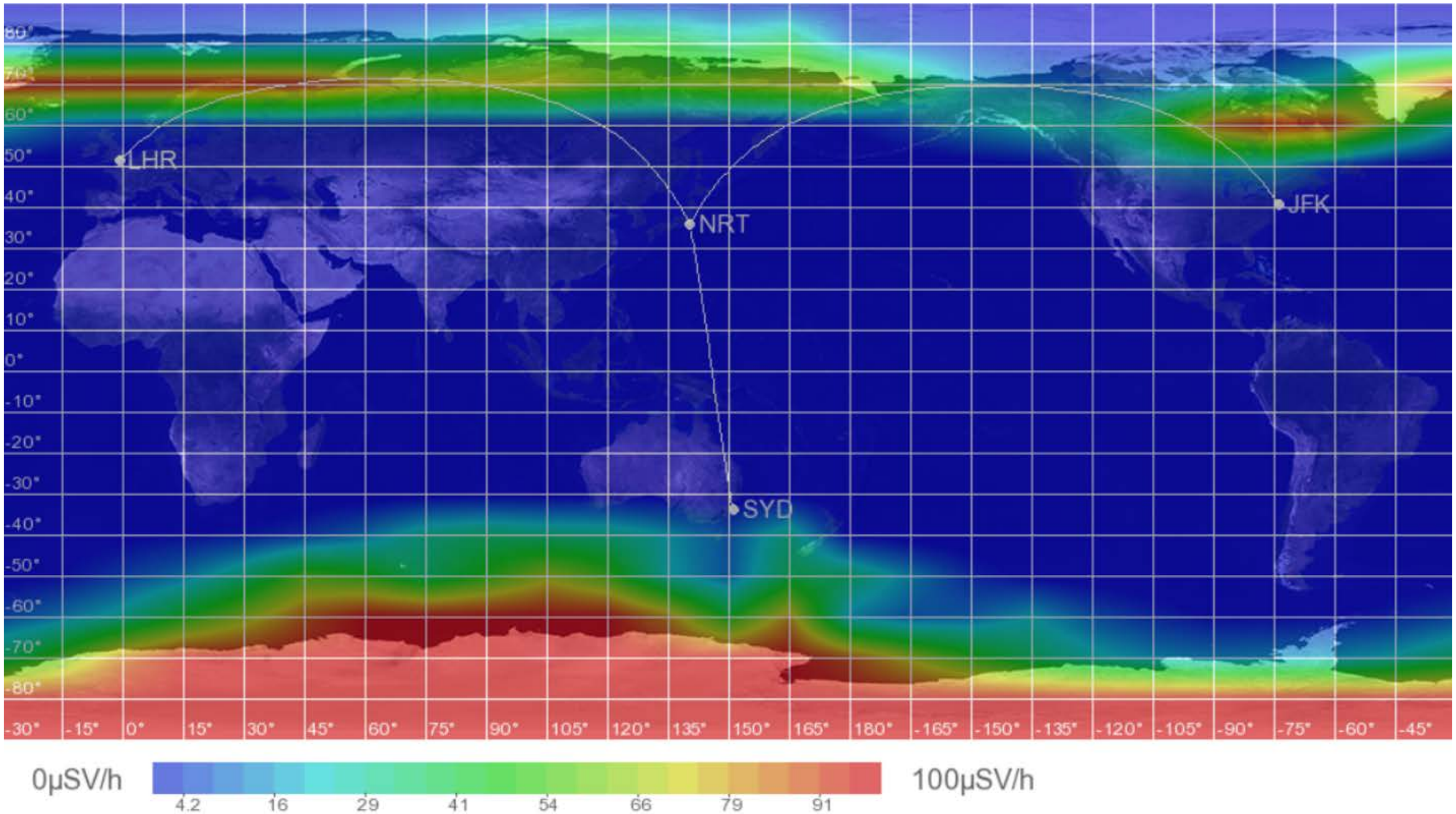
Dose Rate at Conventional Flight Altitude



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

- ✓ $D_{SEP} > D_{GCR}$ at the beginning of GLE 60 & 69
- ✓ $D_{SEP} < D_{GCR}$ 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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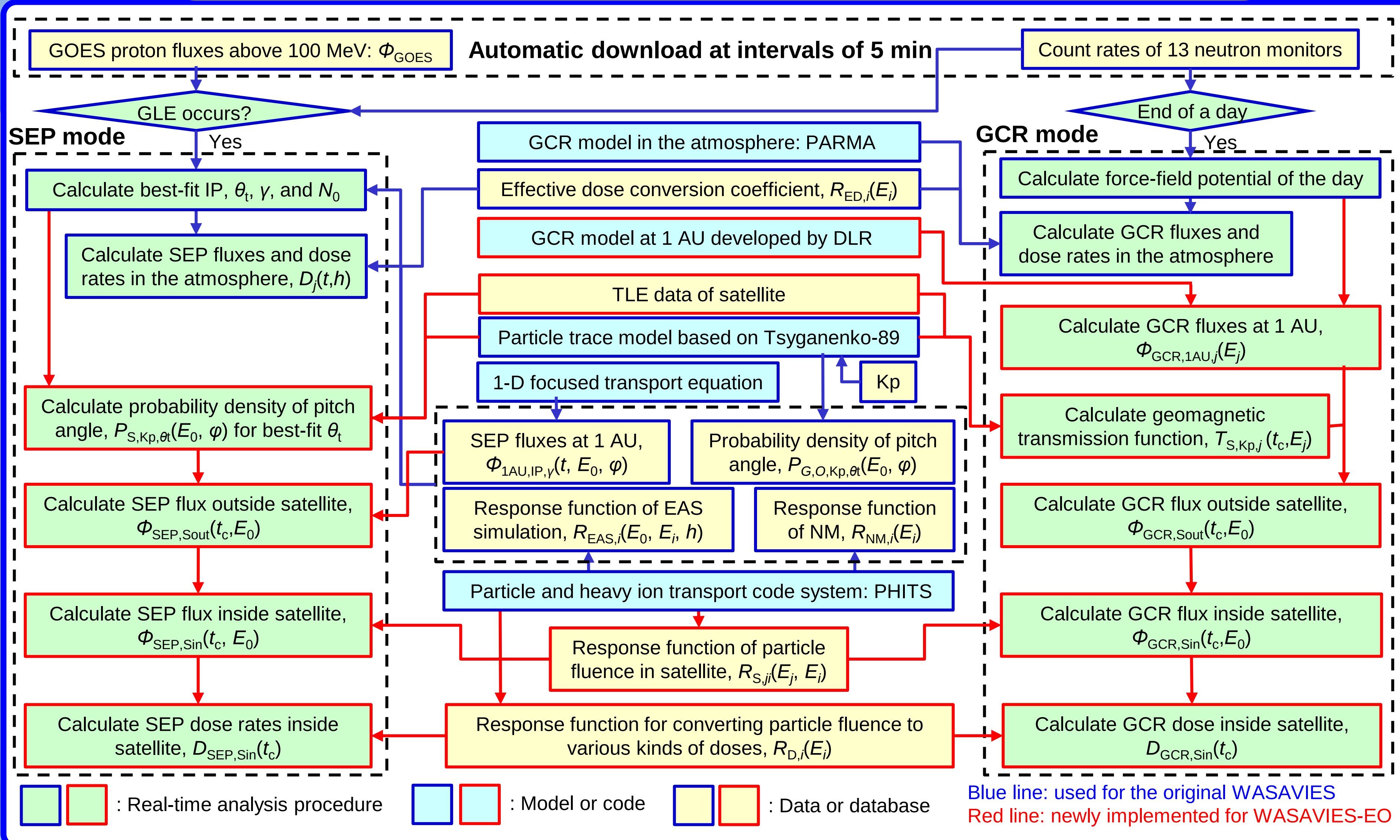
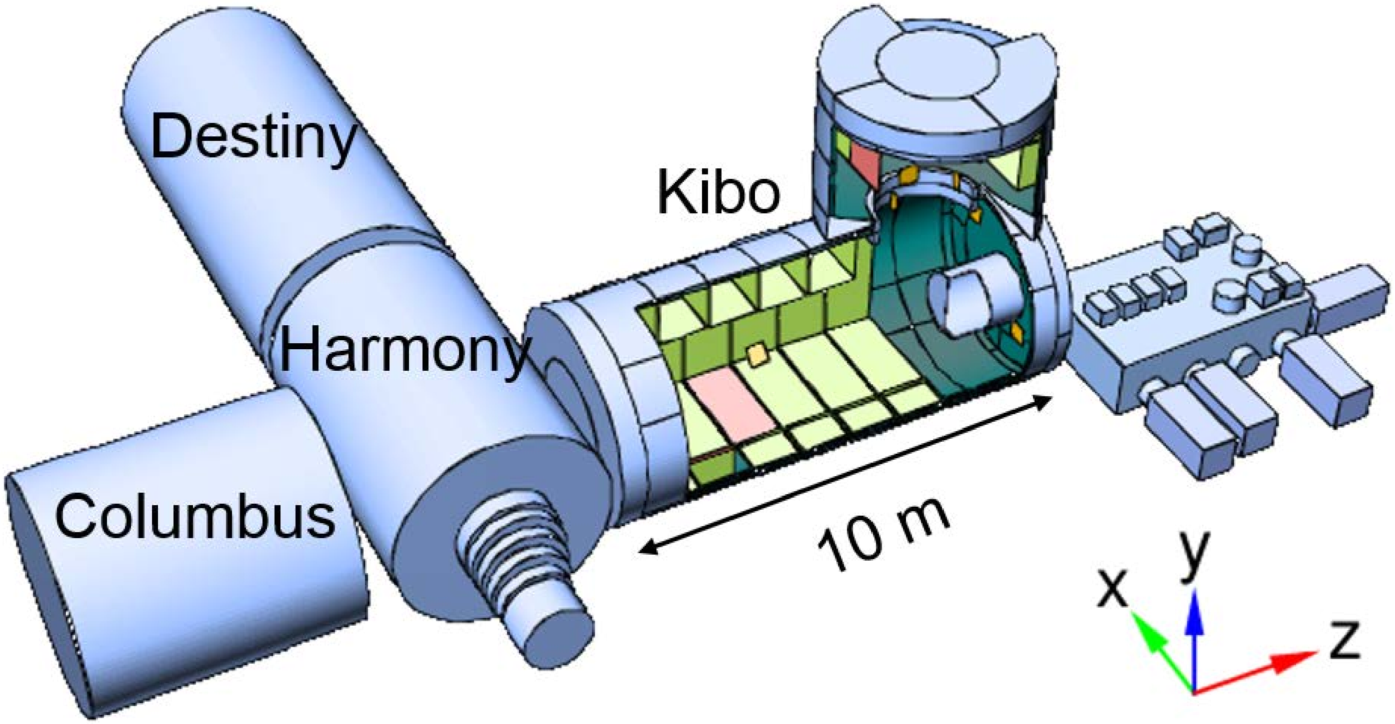
Flowchart of WASAVIES-EO



WASAVIES-EO starts after all analyses of WASAVIES are finished, based on TLE data

Virtual ISS



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/cm^2
- ✓ Response functions in 16 locations in the Kibo module are calculated

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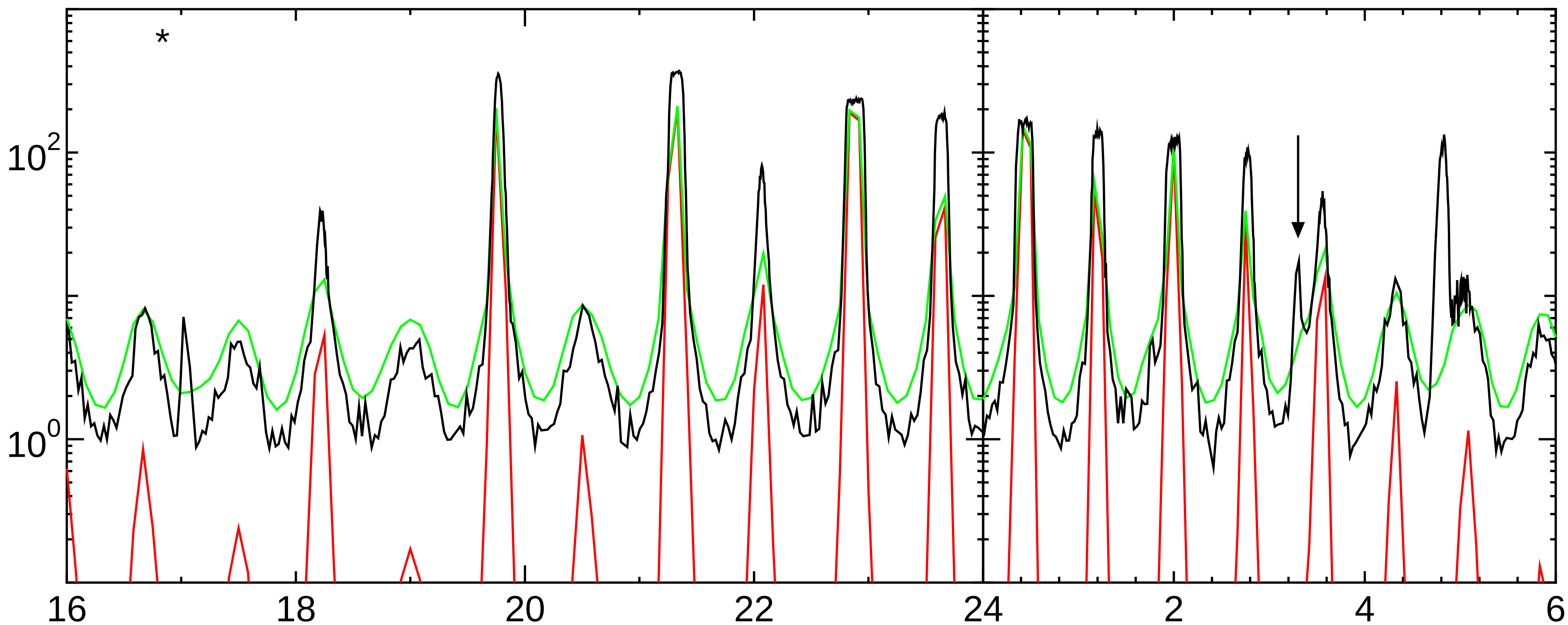
DOSTEL in US Laboratory

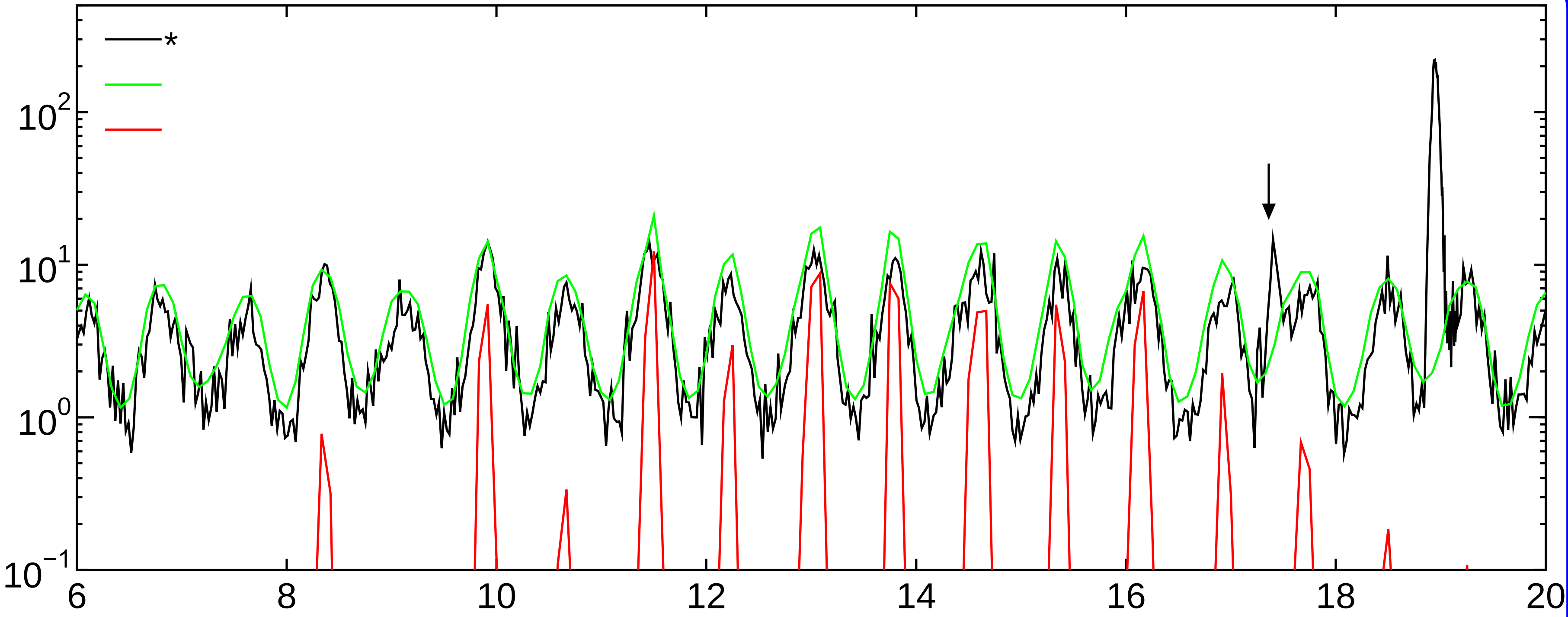


Dose rates measured by Si detector (DOSTEL) in ISS US Laboratory

- ✓ WASAVIES-EO can reproduce GCR dose rates very well
- ✓ SAA peaks are not reproduced because TP contribution was not considered
- ✓ Dcal < Dexp slightly at the SEP peak → difference of shielding configuration

*Reitz et al. 2005, Berger et al. 2018

Liulin-5 in MATROSHKA-R in Russian Module

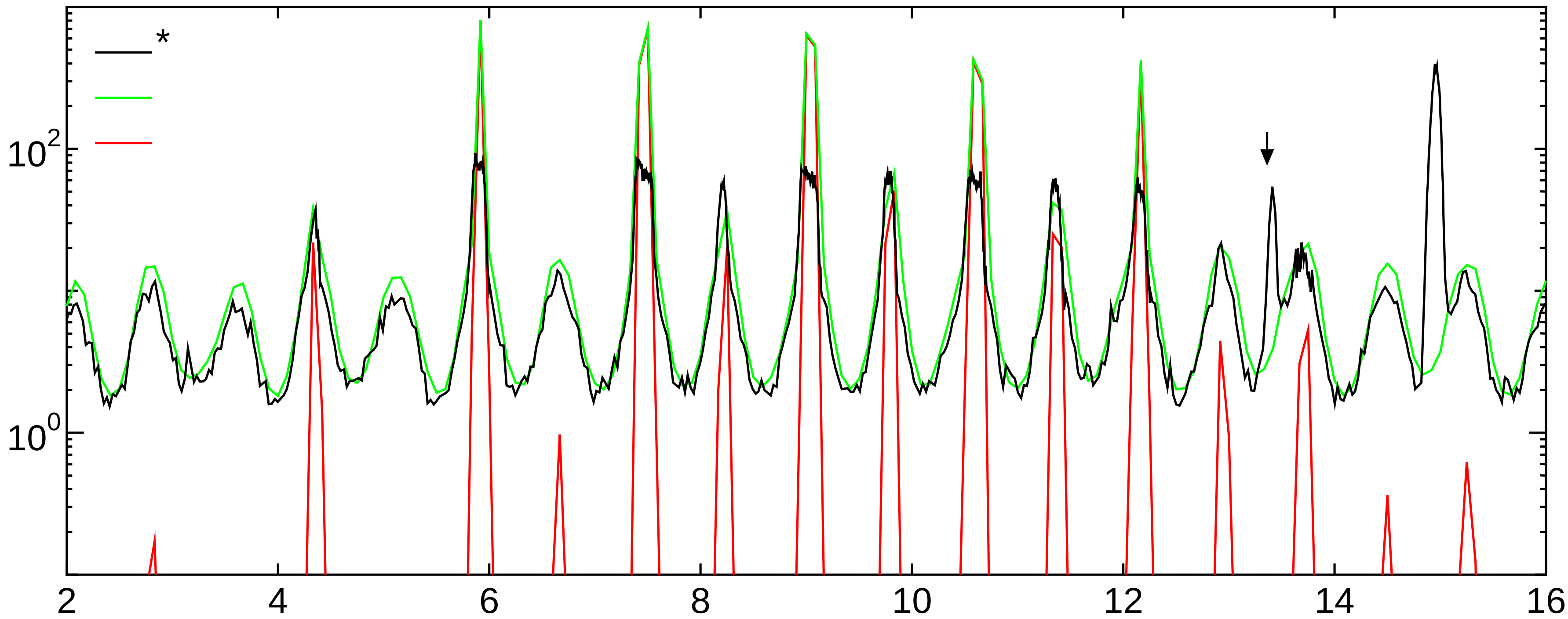


Dose rates measured by Si detector (Liulin-5) in MATROSHKA-R phantom in Russian module of ISS

- ✓ **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

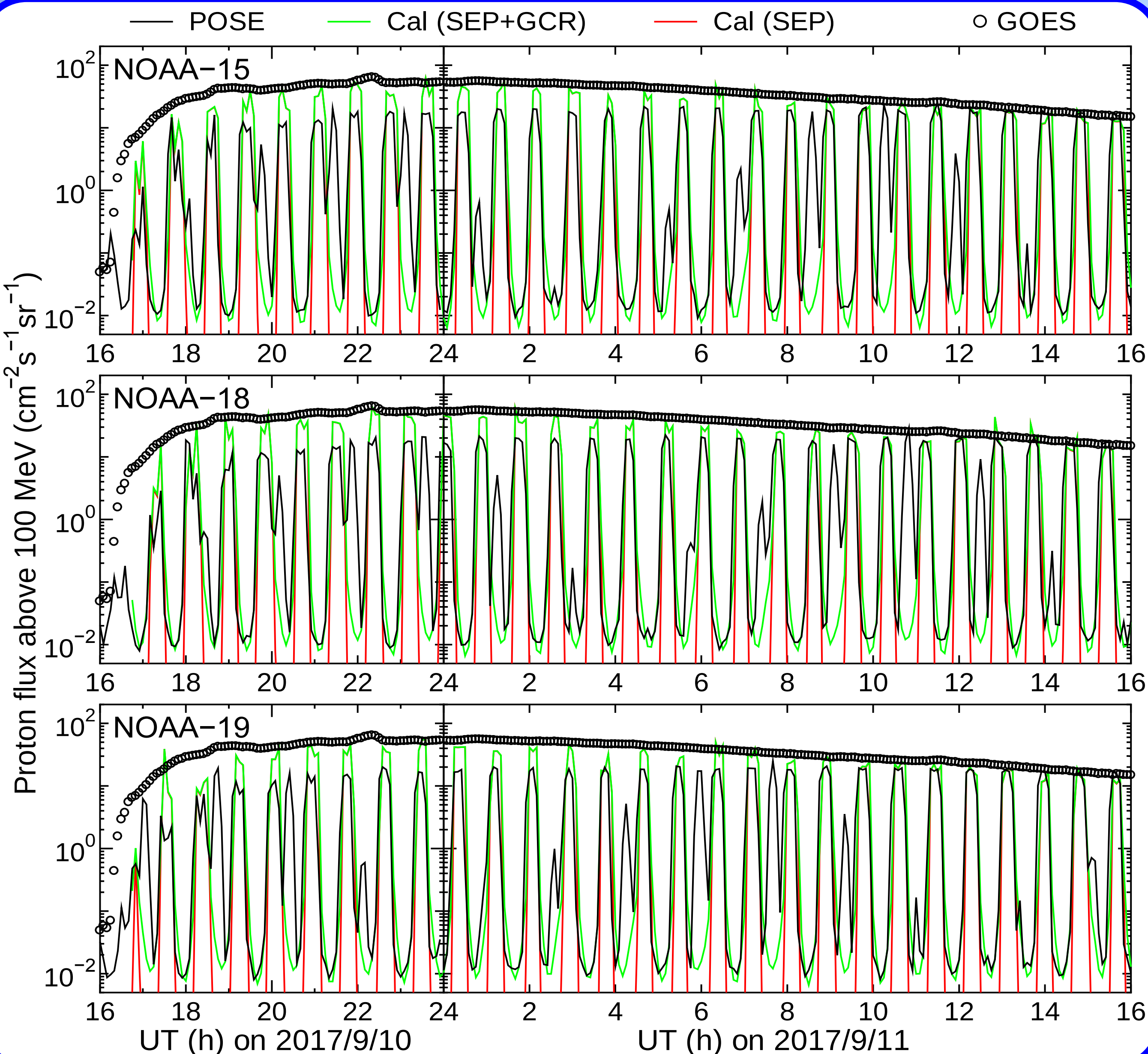


Dose rates measured by Si detector (DOSTEL) in ISS Columbus module

✓ Dcal > Dexp at the SEP peak → difference of shielding configuration or overestimation of low-energy SEP fluxes (E<80MeV)

*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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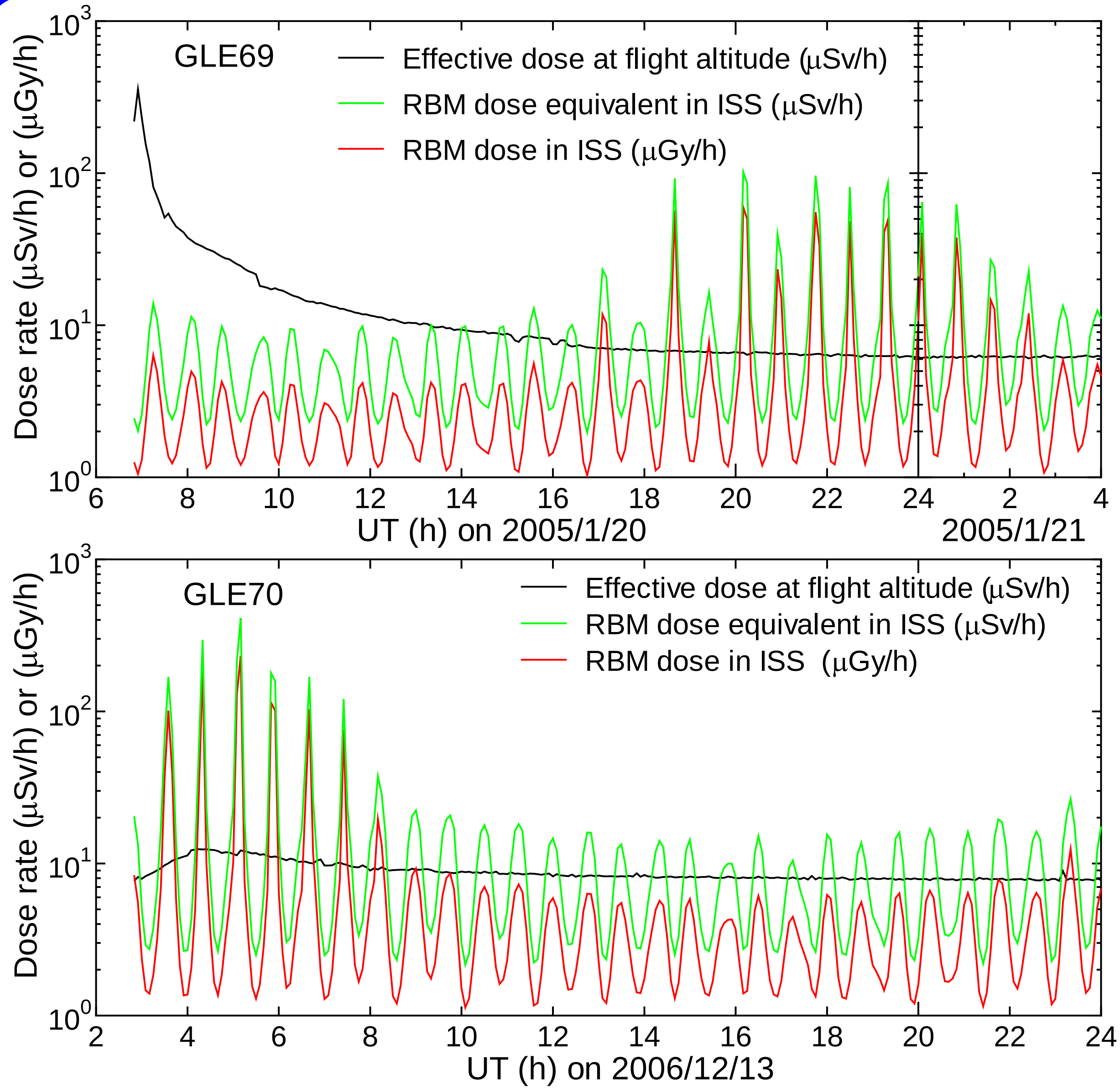
Nowcast radiation doses

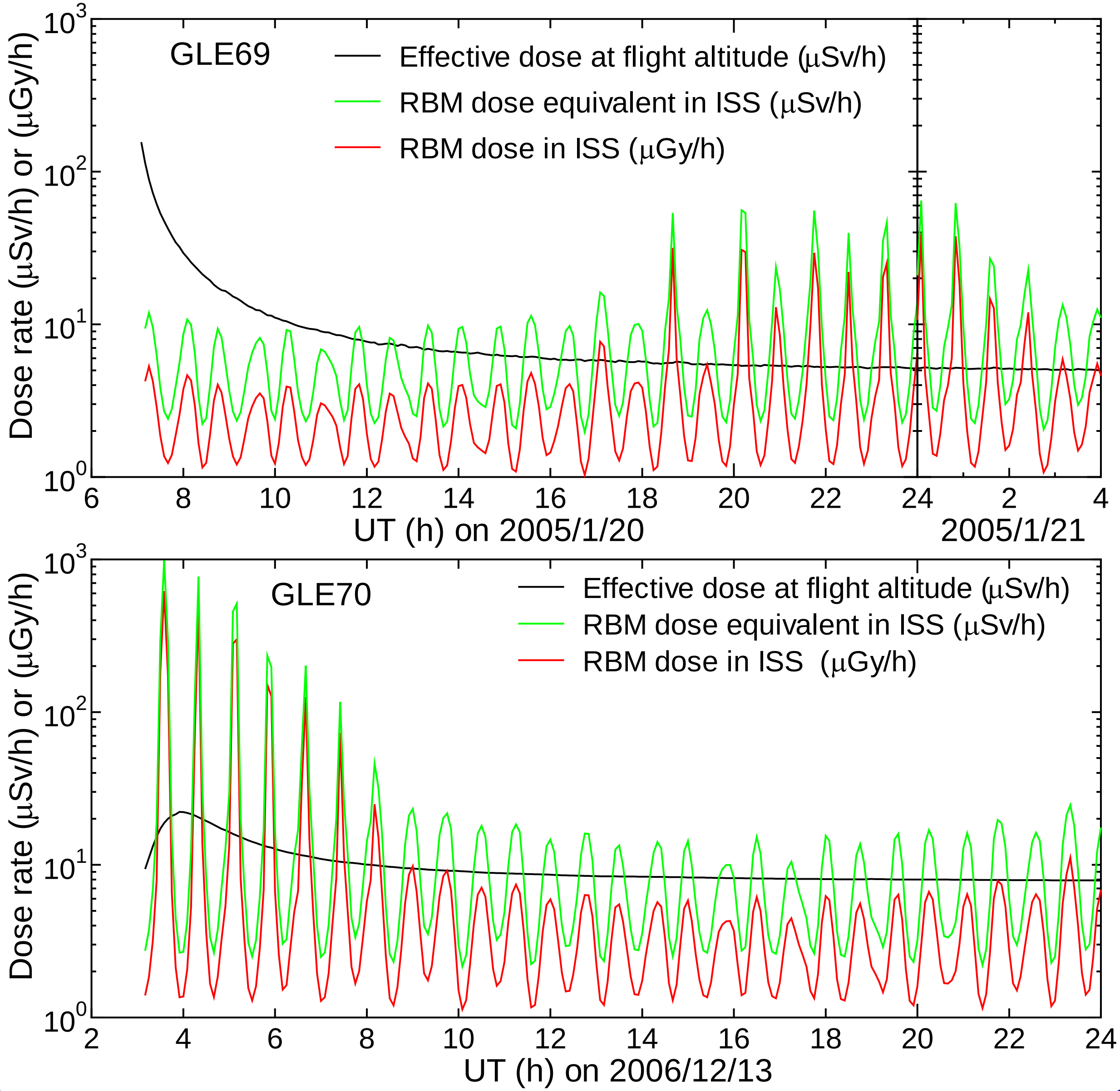


Effective dose at flight altitude and astronaut dose equivalent in ISS during GLE 69 and 70

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

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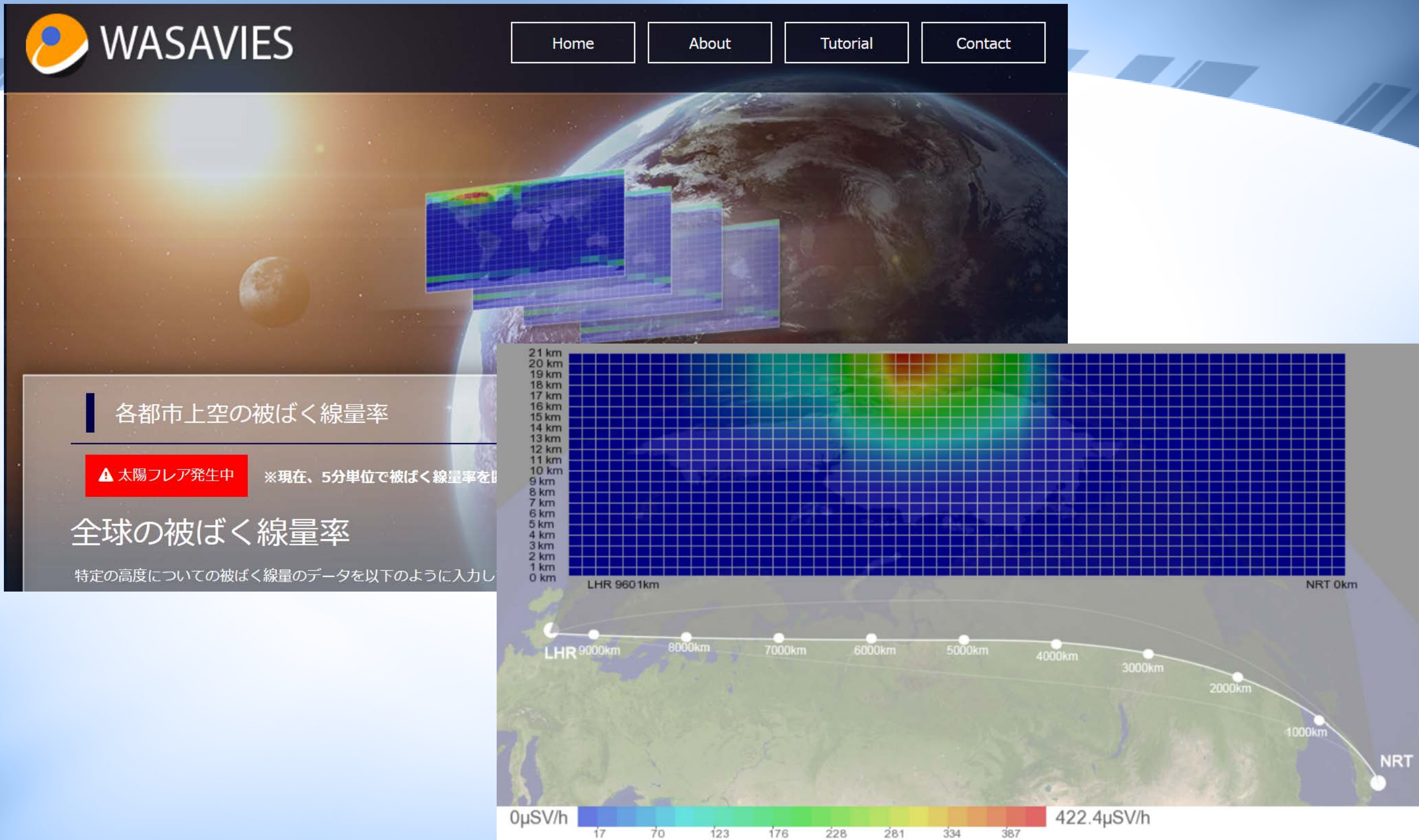
Summary

- ✓ 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

In near Future...



Website of WASAVIES for issuing SEP exposure alert via NICT server

For more detail?

- ✓ Basic features of WASAVIES

  T. Sato et al. Space Weather 16, 924-936 (2018)

- ✓ Application of WASAVIES to GLE72

  R. Kataoka et al. Space Weather 16, 917-923 (2018)

- ✓ Basic features of WASAVIES-EO

  To be submitted within a week or so