A simulation model of the radiation dose measured onboard of the ISS

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Long-term measurements with the R3DE detector, performed outside ISS at the EuTEF facility on Columbus module, supply investigators with amount of data sufficiently large to support activities in developing mathematical models simulating radiation environment of the Station, particularly dose rate. In this work a model, approximating data, into spherical coordinate system, received during certain interval of time, and found to be unexpectedly realistic still simple enough, will be considered.

Description of R3DE instrument

R3DE (Radiation Risks Radiometer-Dosimeter (R3D) for EXPOSE-E facility on European Technological Exposure Facility (EuTEF) outside of European Columbus module of ISS is a Liulin type miniature spectrometer-dosimeter and 4 channels visible and UV spectrometer [1, 2]. Pulse high analysis technique is used for the obtaining of the deposited energy spectrum, which further is used for the calculation of the absorbed dose and flux in the silicon detector.

R3DE instrument was initiated at 20th of February 2008, continuously working till 1st of September 2009 with 10 seconds resolution behind less than 0.4 g.cm^{-2} shielding. This allows direct hits on the detector by electrons with energies higher than 0.78 and protons with energies higher than 15.8 MeV [3]. The surface of the detector is orientated perpendicularly to the "+Z" axis of ISS.

Data analysis

R3DE Latitudinal distribution of the ISS radiation environment components

Figure 1 presents the latitudinal distribution against L-values [4, 5] of the doses along the ISS orbit. On the X axis the L-value is plotted. On Y axis the dose rate measured by R3DE instrument is plotted. The panel cover data from 11th to 21st of July 2008.

Three different radiation sources are easy to distinguish from the data. The major amount of measurements is concentrated in the GCR points (red), which are seen as area with many points in the lower part of the panel in L-values range between 0.9 and 6.2. The covered dosed rate range is between 0.03 and 20-25 µGyh^{-1}. The lowest rates are close to the magnetic equator, while the highest are at high latitudes equatorward from both magnetic poles.

The second source are the protons (green) in the inner radiation belt (RB), which are situated as large maximum in the upper-left part of the panels. They cover the range in L-values between 1.2 and 2.6. This area is usually denoted as the South Atlantic anomaly (SAA) region. The dose rates in the SAA region vary between 10-15 and 1130 µGyh^{-1}. The structure seen inside of the SAA maximum is connected with the different way of crossing of the anomaly by ISS along the orbit. The maximum dose rates of about 1130 µGyh^{-1} are observed at this region.

The wide maximum in L-values between 3.5 and 6.2 is connected with the observations of rare sporadic Relativistic electrons (blue) precipitations (REP) generated in the outer RB [6, 7]. These points are excluded by the simulations.

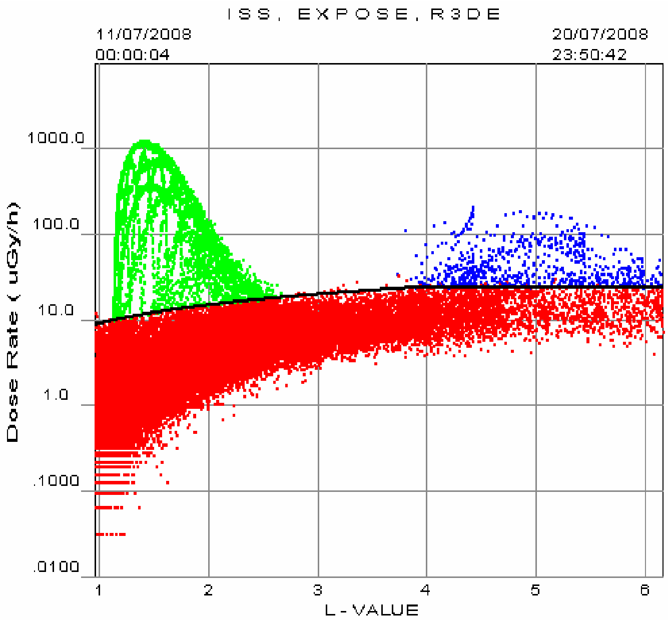

Fig.1. Invariant latitude profile of the ISS radiation environment

Mathematical background

Associated Legendre functions and Spherical harmonics

First some basic definitions have to be introduced here following [8]. Functions of the type

$$P_n^{(m)}(x) = \sqrt[m]{1-x^2}\,\frac{d^m P_n}{dx^m}, -1 \le x \le 1$$

where $P_n(x) = \dfrac{1}{2\pi}\displaystyle\int_0^{2\pi}\left[x + i\sin\varphi\sqrt{1-x^2}\right]^n d\varphi$

are called associated Legendre functions (or polynomials) of mth order. Obviously $P_n^{(0)}(x) = P_n(x), P_n^{(m)} \equiv 0$ *if m>n.*

These functions are most useful when the argument is reparameterized in terms of angles, letting $x = \cos\theta$:

$$P_n^m(\cos\theta) = (\sin\theta)^m \frac{d^m}{d(\cos\theta)^m} P_n(\cos\theta)$$

Now spherical harmonics could be defined as follows:

$$Y_n(\theta,\varphi) = \sum_{m=0}^{n}\left(A_{nm}\cos m\varphi + B_{nm}\sin m\varphi\right)P_n^{(m)}(\cos\theta),$$

where $0 \le \theta \le \pi$, $0 \le \varphi \le 2\pi$. *Here* A_{nm} *and* B_{nm} *are Fourier coefficients given by:*

$$A_{nm} = \int_0^{2\pi}\int_0^{\pi} f(\theta,\varphi) P_n^{(m)}(\cos\theta)\cos m\varphi \sin\theta d\theta d\varphi$$

$$B_{nm} = \int_0^{2\pi}\int_0^{\pi} f(\theta,\varphi) P_n^{(m)}(\cos\theta)\sin m\varphi \sin\theta d\theta d\varphi.$$

Then, supposing $f(\theta,\varphi)$ being an arbitrary continuous function defined on the sphere, two times continuously differentiable as well, permitting decomposition by means of spherical harmonics, the following statement holds:

$$f(\theta,\varphi) = \sum_{n=0}^{\infty} Y_n(\theta,\varphi) \approx \sum_{n=0}^{N} Y_n(\theta,\varphi),$$

where N should be sufficiently large to obtain required accuracy of the approximation.

Implementation of the method

Creating array to be approximated

Here some assumptions about how mathematical method, described above, was applied to create a computer model of radiation dose, measured during the second half of the year 2008. Only red and green components (Please see Figure 1) were counted.

Orbiting around the Earth, ISS performs its measurements on a surface, that can be described as spherical ring, $|\text{latitude}| < 51.8^0$. The problem to discus here is how to estimate linear dimensions of a rectangular sell in order to create net of sells covering this ring, each sell containing mean value of the measured dose inside it.

In practice, when discrete measurements on the sphere are given, quadrature methods are required to obtain spherical harmonic coefficients A_{nm} and B_{nm}, therefore some obvious requirements to the sampling in both directions of the array containing data have to be considered. Another reason to care about dimensions is the necessity for continuity mentioned above. Of course, any discreet function should be considered as continuous, but there remain the problem of the steepness (or gradient) of the signal. In fact, at the northern border of SAA, along the meridian, the signal increases more than 100 times into very short interval, from north to south, i.e. the gradient is very big. Consequently, as far as Fourier series performs a least squire fit, such an approximation usually produces large errors at the point of jump of the signal, known as "effect of Gibbs", which is highly unacceptable. Thus, decreasing "latitudinal" dimensions of the sell will generate enlargement of the gradient which must be avoided, while increasing of this dimension will reflect as unnatural smoothing of the peak values in SAA. However, keeping in mind that this work should be considered as a preliminary one, and that its purpose is to answer the question whether the mathematical method works well with such kind of data rather than achieving an impressive accuracy, the accepted sell attributes were 0.5^0 by latitude and 1^0 for longitude. Sizes of the net sells affect other phenomena as well: a sell will be filled with a series of observations when ISS trajectory crosses this area and the length of such a series depends of the nearness to the equator. Note that we have to choose degree as measurement units because independent variables are angles (θ, φ). So the surfaces of the sells are different relatively to latitude. Computational results

Following the above considerations, observations were gathered into array dimensioned (I_{rows}, $J_{columns}$)=(207, 360). During the process of gathering of the data basic statistical parameters, mean and standard deviation, for each sell were computed in order to exclude erroneous measurements from computations. The elements of the array were converted to log scale in order to decrease steepness around SAA.

In this work a model of order N=91 is presented. The result is presented graphically on Figure 2.

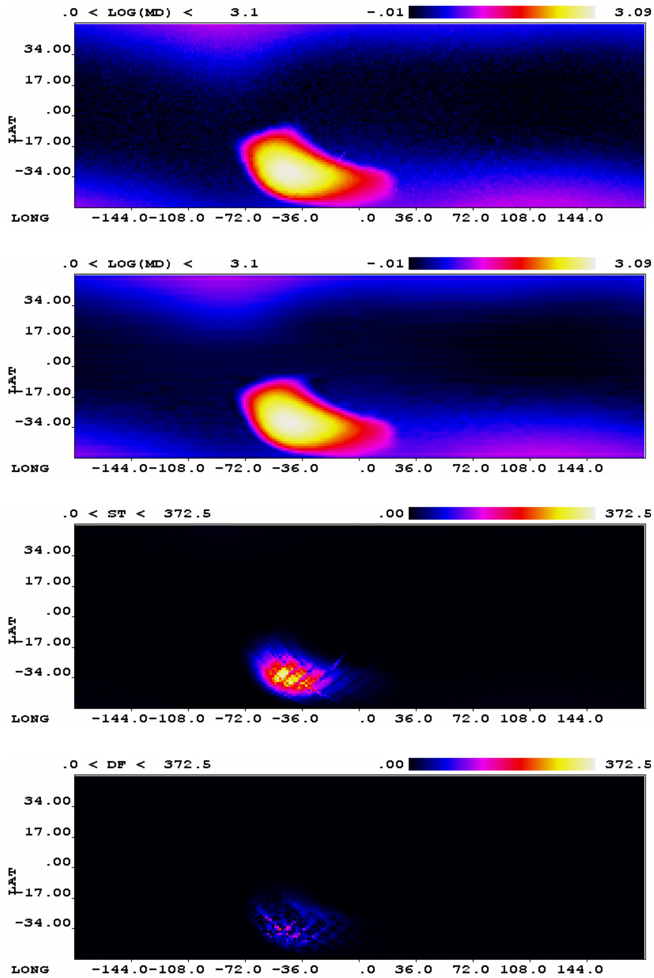

Fig.2. 1st panel consists the real measured data, 2nd the modeled data, 3rd standard deviation and the 4th the differences between model and raw data

Figure 2 consist of 4 panels, which gives the global distribution in geographic coordinates – longitude in the range -180°-180° and latitude -51.8°-51.8°. The upper panel present a plot of raw dose rate measurements stored into array explained above. The next panel presents the results of the calculated by the model values in same dimensions. Both plots are in log scale. The remaining two panels are related to the accuracy – first of them presenting standard deviation of the raw data and second one is a plot of the absolute values of the difference, sell by sell, between computed model data and that of the array with real data.

Discussions

The obtained by the model dose rate shown in the second panel represent very well the measurements in the first panel in all longitudes and latitudes.

Results shown on the standard deviation panel (second from bottom) have to be discussed first. Obviously, the deviation level near to the maximum of the signal turns to be very large, almost 30% of the max value of the dose rates in the SAA. Noise should be excluded from the set of possible explanations of the phenomena as far the instrument prove to work properly. Thus, some additional independent variable (or variables) should be added to the model to spread data into subsets where statistical properties of the signal will be more convenient for further processing. To realize the idea longer initial interval of measurements is needed. However, as it could be seen from the bottom panel, average error is less then 5% almost everywhere in the SAA except for few points, where difference between model values and real one is bigger but still less than 10%.

Conclusion

This very simple model, based only on the angular coordinates of the observation, could be useful, at least as a first approach to the problem of modeling such measurements.

Further development of the model will include the altitude as independent parameter. Also a user friendly interface will be developed, which will allow all interesting including general public to work with the model and to obtain relevant reasults.

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