DEVELOPMENT OF A SPACE RADIATION MONTE-CARLO COMPUTER SIMULATION BASED ON THE FLUKA AND ROOT CODES

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INTRODUCTION

The radiation environment in space is a complex problem to model. Trying to extrapolate the projections of that environment into all areas of the internal spacecraft geometry is even more daunting. With the support of our CERN colleagues, our research group in Houston is embarking on a project to develop a radiation transport tool that is tailored to the problem of taking the external radiation flux incident on any particular spacecraft and simulating the evolution of that flux through a geometrically accurate model of the spacecraft material. The output will be a prediction of the detailed nature of the resulting internal radiation environment within the spacecraft as well as its secondary albedo. Beyond doing the physics transport of the incident flux, the software tool we are developing will provide a self-contained stand-alone object-oriented analysis and visualization infrastructure. It will also include a graphical user interface and a set of input tools to facilitate the simulation of space missions in terms of nominal radiation models and mission trajectory profiles.

The goal of this project is to produce a code that is considerably more accurate and user-friendly than existing Monte-Carlo-based tools for the evaluation of the space radiation environment. Furthermore, the code will be an essential complement to the currently existing analytic codes in the BRYNTRN/HZETRN family for the evaluation of radiation shielding [1]. The code will be directly applicable to the simulation of environments in low earth orbit, on the lunar surface, on planetary surfaces (including the Earth) and in the interplanetary medium such as on a transit to Mars (and even in the interstellar medium). The software will include modules whose underlying physics base can continue to be enhanced and updated for physics content, as future data become available beyond the timeframe of the initial development now foreseen. This future maintenance will be available from the authors of FLUKA as part of their continuing efforts to support the users of the FLUKA code within the particle physics community. In keeping with the spirit of developing an evolving physics code, we are planning as part of this project, to participate in the efforts to validate the core FLUKA physics in ground-based accelerator test runs. The emphasis of these test runs will be the physics of greatest interest in the simulation of the space radiation environment.

Such a tool will be of great value to planners, designers and operators of future space missions, as well as for the design of the vehicles and habitats to be used on such missions. It will also be of aid to future experiments of various kinds that may be affected at some level by the ambient radiation environment, or in the analysis of hybrid experiment designs that have been discussed for space-based astronomy and astrophysics. The tool will be of value to the Life Sciences personnel involved in the prediction and measurement of radiation doses experienced by the crewmembers on such missions. In addition, the tool will be of great use to the planners of experiments to measure and evaluate the space radiation environment itself. It can likewise be useful in the analysis of safe havens, hazard migration plans, and NASA's call for new research in composites and to NASA engineers modeling the radiation exposure of electronic circuits. This code will provide an important complimentary check on the predictions of analytic codes such as BRYNTRN/HZETRN that are presently used for many similar applications, and which have shortcomings that are more easily overcome with Monte Carlo type simulations. Finally, it is acknowledged that there are similar efforts based around the use of the GEANT4 Monte-Carlos transport code currently under development at CERN. It is our intention to make our software modular and sufficiently flexible to allow the parallel use of either FLUKA or GEANT4 as the physics transport engine.

I. Analytic and Monte Carlo-Based Codes

Since the 1960's many different radiation transport simulation codes have been developed [2-8]. The diversity in this development is the result of the wide variety of applications for which these codes are employed. These include uses as diverse as the estimation by NASA of flight crew radiation doses and the related problem in cancer treatment of estimating the delivered therapeutic radiation dose, to the use of these codes in the evaluation of data in accelerator-based elementary particle physics experiments. Indeed, the group at NASA/Langley under the able direction of Townsend and Wilson have played a lead role in the development of one of the most heavily used tools in routine use by NASA for this simulation problem [1]. Their work has pioneered what is termed the *analytic* method in contrast to the *Monte-Carlo* method. The Monte Carlo method has evolved in and become more widely used in the world of experimental particle physics. The present study is in the process of developing a new integrated Monte-Carlo software package, specifically tailored for use in the simulation of the space radiation environment, to address design problems, astronaut dosimetry calculations, and astrophysical payload design. The new code is to be based upon the melding together of two existing evolving codes, FLUKA [2-3, 5, 9-14], a Monte-Carlo radiation transport program, and the object-oriented physics analysis infrastructure known as ROOT [15-16].

In the early years of manned spaceflight the need existed then as now to predict and evaluate the effect of shielding on the radiation that flight crews are exposed to in space [17-20]. The choice of technique was driven in earlier times by the relatively modest capability of available computing power. Over the intervening years, with the exponential growth in both the hardware and software capability, the potential for extending the Monte-Carlo technique into applications that had once been impractical, has now become feasible. While there is still a clear need to pursue the development of both techniques, as recognized recently in the recommendations from the NASA sponsored Workshop on Predictions and Measurements of Secondary Neutrons in Space (NASA/JSC, 28-30 September, 1998) [21], the analysis discussed here is specifically directed towards the need to provide a state-of-the-art Monte-Carlo based code. The uses for the proposed radiation transport simulation that are of interest to the NASA community go well beyond just providing a complimentary technique for the evaluation of the radiation doses endured by

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both crews and hardware (NASA's Code U). They also include the ability to provide detailed simulation of experiments such as the ACCESS (Advanced Cosmic Ray Composition Experiment for the Space Station) experiment that is currently being considered for deployment on the ISS (NASA's Code S). (The ACCESS Home Page may be viewed at http://www701.gsfc.nasa.gov/access/access.htm). This latter type of application is the sort for which the analytic type tools are least well suited, and for which the Monte-Carlo type are most beneficial.

II. FLUKA

FLUKA was originated by Professor Johannes Ranft beginning in 1970 for simulating particle cascades (FLUKA is acronym formed from the German for "Fluctuating Cascade") [22-25]. Professor Ranft has ceded control over the continued development of FLUKA to the INFN (Instituto Nazionale di Fisica Nucleare—the Italian National Nuclear Physics funding agency) group at the University of Milan. The individuals primarily responsible are a husband and wife team, Drs. Alfredo Ferrari and Paola Sala. Dr. Federico Carminati, who is currently the simulation coordinator for ALICE (the heavy-ion experiment being built for the Large Hadron Collider [LHC] project at CERN) is also a key person in the evolution of FLUKA. He was previously the manager for GEANT at CERN and he was responsible for porting FLUKA to the UNIX (including LINUX) operating system from VMS.

FLUKA is also a "biased" code. That is, FLUKA is designed to allow internally for the biasing in favor of the occurrence of rare events. This provides for their simulation at a higher than normal frequency. Such a feature allows the user to acquire statistics on rare events much faster than in linear codes. FLUKA automatically keeps track of this accounting and can do so for all of the internally simulated physics as well as for external packages. Thus, one does not have to play with the inputs and do off-line recombinations to assemble the outputs.

Further, FLUKA embeds the technology for simulating the transport of low-energy neutrons developed over 30 years by the nuclear reactor community. The cross-section libraries have been based upon the most recent data from JEF-1, JEF-2.2, ENDF/B-VI (the most recent compilations from Los Alamos), and JENDL-3. More than 60 different materials are included with temperature ranges extending down to cryogenic temperatures. This code has been used extensively to model the neutron environments near high energy physics experiment shielding and the associated databases, and can easily be updated when new compilations become available. FLUKA also embeds the well-known EGS code mentioned above to treat electromagnetic interactions. Ralph Nelson from SLAC, the principal party responsible for the EGS code, has publicly declared that FLUKA's implementation of EGS IV is "the best version of EGS IV on the market." FLUKA is arguably the most accurate integrated simulation available at the present time. Recently the ATLAS collaboration from the LHC project at CERN did a side-by-side comparison of all of the available Monte-Carlo codes and concluded at least for calorimetry applications that FLUKA is the best currently available code. Finally, FLUKA, is a maintained and updated code that can be expected to improve continuously over the foreseeable future. Information on FLUKA is also available at http://www.mi.infn.it/~battist/fluka.html.

Given FLUKA's comparative excellence as a radiation transport code, the question arises as to what modifications are required to make it useful for the routine simulation of the space radiation environment? First, although the FLUKA team is in the process of adding the complete range of heavy-

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ion interactions needed to simulate the propagation of the heavy cosmic rays, it is not their highest priority, and assistance is needed to facilitate that implementation. Other physics improvements will be incorporated in the core physics code by the FLUKA team as they become available. Such enhancements will also continue to occur beyond the time of this proposed project's conclusion.

Secondly, since the FLUKA code was first designed, there has been substantial progress in the development of 3-D geometry software. Driven by computer graphics technology and ray-tracing applications, many new 3-D geometry packages are available. There is considerable room for improvement in the present geometry package used in FLUKA. The benefits of such an improvement would include an increase in the calculation speed during propagation simulations, and the additional bonus of easy access to industry-standard input and graphic display formats. The FLUKA team is interested in working with this proposed project to implement such an improvement.

However, beyond the need for some physics additions and internal geometry enhancements, the major reason that FLUKA is not more widely used is the awkward nature of the present interface to the code. Admittedly, the current input format is archaic and limited. Furthermore, the tools available to structure the form of the output are also limited and difficult to use. To address these limitations, the thrust of the project proposed here is to meld FLUKA together with the recently released physics analysis infrastructure known as ROOT. This task will require an intimate conversion of the FLUKA data structures as opposed to the simple serial attachment of one code to another.

III. ROOT

ROOT, which is rapidly becoming a major force in the world of particle physics analysis software, is the product of Dr. Rene Brun of CERN [15]. Dr. Brun is widely known in the particle physics software community. He is the original author of GEANT 3.21 and was the director of analysis software development at CERN for many years. In fact Tim Berners-Lee developed the World-Wide-Web while working under Dr. Brun at CERN. Dr. Brun also developed the widely used PAW (Physics Analysis Workstation) software tools.

Dr. Brun initially embarked on the project known as ROOT to address the specific limitations of PAW. However, during its development ROOT evolved into much more than a simple update of PAW. It has become not only an analysis and a visualization software program in one package, but a complete data handling infrastructure. At its heart, ROOT is based upon Object-Oriented (OO) data structures. This use of OO programming allows many difficult tasks with multiple uses to be done only once. For example, after the task of inputting the complex geometry of the ISS is done once, that same information can be used seamlessly as the input for the Monte- Carlo transport calculations. The same data structure can then be applied to visualizations of individual Monte Carlo events in a fly-through 3-D event viewer, or for choosing regions to provide plots of individual summed parameters. In fact, it can be employed for any analysis or display uses that need to specify or depict some portion of or indeed the entire structure in question. The best feature of ROOT is that much of the manipulation is provided via GUI (Graphical User Interface) menus and displays. Further, when special features need to be added, ROOT uses C++ as a scripting language. This implementation of the scripting language allows the user to create structures and functions that blend seamlessly into ROOT, providing a real user-extension of the system. Moreover an intelligent pre-

processor completely solves the problem of persistency of objects in disk storage. ROOT features and examples can be viewed on the Web at http://root.cern.ch. That site also contains the downloadable software with accompanying tutorials.

IV. Description of the Current Project

The goal of this study is to produce a well-documented code that can be widely distributed and employed by a variety of users. It is anticipated that the core project will be completed within three years.

In addition to the development of the code itself, databases will also be included to allow ease of simulation of the ambient radiation environment in space. Models of the trapped radiation, the galactic cosmic radiation, the modulation effects of the solar cycle, the albedo from the Earth's atmosphere, and a variety of solar flare examples will be included. Tools will be provided to allow users to tailor the inputs to specific mission profiles.

To accomplish our immediate task we would have liked to be able to modify the geometry package within FLUKA. However, a funding shortfall from our requested amount has lowered this task in priority. We are also limited due to the funding shortfall on the amount of FLUKA calibration we will be able to accomplish. We are proceeding to modify FLUKA to include heavy ion interactions and as needed for use with ROOT inputs. The result will be a combined package that will allow the use of the ROOT interface to input to and control FLUKA, and then seamlessly continue within ROOT to do the analysis of the output from FLUKA. Our approach will be generic and it will allow the developed infrastructure to be readily adapted to the use of any Monte Carlo transport code that allows independent subroutine calls for histogramming. Such a package will be useful not only for the final analysis of the eventual end product output, but it will be invaluable for iterative development of the simulation itself. Integrated single-event displays and the ability to examine the performance of the simulation in geometric as well as physics detail, will be of great benefit in providing rapid and efficient application of the code to the variety of tasks for which it is being developed. The analysis software can even be employed within the ROOT framework to create, fill and plot histograms during the actual data taking, allowing one to perform classical statistical analysis on them, including multi-parametric fits in real-time.

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