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Abstract—To ensure the health of space personnel and the cost-efficiency and safe-operation of space materiel and equipment, we performed a preliminary investigation to find ways to apply high-performance and parallel computer techniques to enable more speedy, accurate, efficient, and user-friendly space radiation studies—modeling, analysis, simulation, and visualization—for Mars missions and current and future space missions. The need to modernize NASA radiation codes is understood. We are currently obtaining the code and seeking support to restructure the computation to match newly developed computer resources of parallel, multithread, network cluster and reconfigurable parallel FPGA platforms. The success of applying parallel techniques to enhance deterministic HZETRN and stochastic FLUKA Monte Carlo radiation transport analysis/ simulation codes used by NASA scientists will greatly enhance space radiation understanding. This research is also vital to safer nuclear energy and anti-aging, cancer treatment with applications in the public sector.

High-Performance Martian Space Radiation Mapping

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TO PROTECT THE HEALTH OF SPACE PERSONNEL AND TO ensure the safe-operation of space materiel and equipment, we carried out a preliminary investigation to find ways to apply high-performance and parallel computer techniques to enable more speedy, efficient, and accurate space radiation simulations for the analysis of Mars missions and and other current or future space missions. While studying the current execution mode and the platform of NASA HZETRN[1] space radiation transport analysis methods, our contact at NASA Langley Research Center verified the "huge" needs to modernize the code to take advantage of the newly developed computer technologies that may run programs faster, more accurately, and with more user-friendly technology. We are currently obtaining the actual code and seeking support to (1) analyze parallel computation threads, (2) schedule computation threads to parallel processor resources, (3) update the core interpolation and integration routines of the code, and (4) port to MPP, cluster, or reconfigurable parallel FPGA platforms. While deterministic space radiation transport code such as HZETRN can produce faster, but approximated, results, it is imperative to also study the complementing, much more accurate, stochastic Monte Carlo space radiation transport simulation FLUKA code for improvement.

Mars Radiation

With any practical amount of shielding during Mars missions, every body cell in an astronaut would still be traversed by at least one heavy ion and several hundred protons. Such space radiation, primarily caused by Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP), is very distinct from terrestrial radiation (x-ray or gamma-rays) with unknown risk to human health, as shown in Cucinotta.[2] Unlike Earth, thin atmosphere and lack of global magnetic field make Mars extremely vulnerable to harmful radiation. Therefore, direct measurements of radiation levels (including the relative contributions of protons, neutrons, and heavy ions) and of Martian atmospheric characteristics are a pre-requisite for any human mission.

Space Radiation Risk

For over 35 years, NASA's radiation simulation and analysis group has long been burdened with great responsibility to assess and certify mission duration for all astronauts and equipment. Research to analyze, model, simulate, and visualize space radiation is critical to predict human risk. Possible health risks from space radiation for long-term space travel include cancer, cataracts, acute radiation sickness, hereditary effects, and damage to the central nervous system.[3] Understanding the space radiation environment is essential for risk assessment of orbit and selection of the crew and provides a scientific basis of countermeasures comprised of shielding materials, radio-protectants, and pharmaceuticals.

Complex Radiation Computation

Research is being performed to mathematically model high-energy particles as they pass through the walls of a spacecraft as well as parts of the human body. Data have been collected over the years on the effects of space radiation on humans[4] but to understand the effects for many different cases, a mathematical model needs to be created to simulate different conditions in space. As a complex computation written in FORTRAN, NASA's current space radiation code is facing greater challenge than ever, comprising a large amount of data gathered from Martian Rover daily in addition to the data collected since 2001 by Mars Odyssey Orbiter.[4] Comparable to scientific weather forecasting and ocean simulation, the task of visualizing the space radiation map of the entire Martian atmosphere plus the interplanetary space between Mars and Earth, is a tremendous undertaking. Japanese attempts for ocean simulation resorted to a giant supercomputer that occupied an area four times the size of a football field.

Parallel Radiation Analysis Enhancement

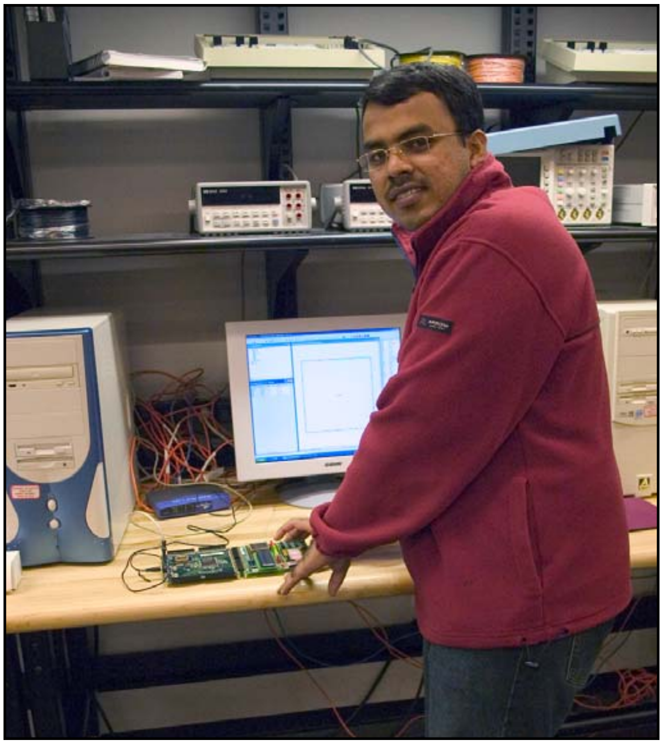
A promising key solution would be to restructure the computation to match the newly developed resource of parallel, multithreading network cluster computers and reconfigurable parallel FPGA platforms. Our preliminary investigation is to study the current execution mode or platform of NASA space radiation code, to determine the feasibility of finding a high-performance and parallel improvement that will bring us to Mars sooner, at lower expense, and safely.

HZETRN Radiation Transport Analysis

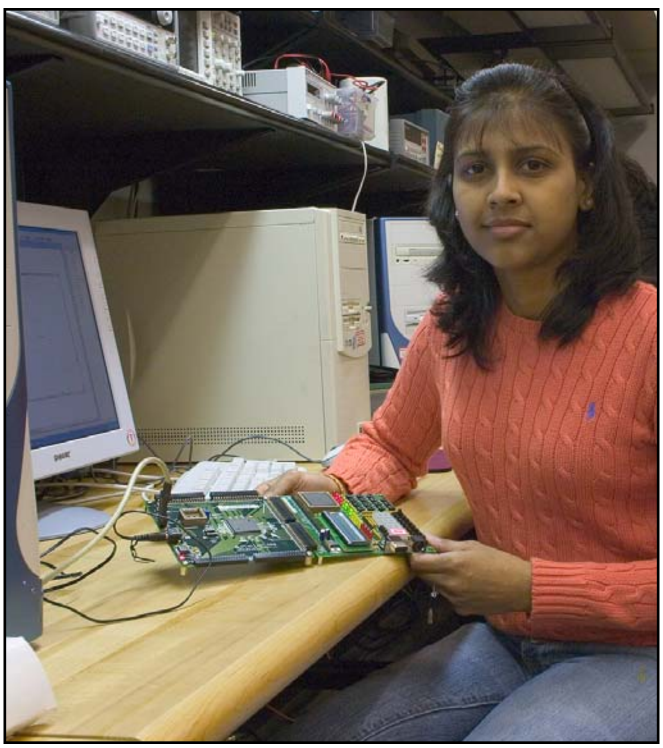
Limited Speed and Accuracy—HZETRN is a Fortran program designed to model the transport of high-Z and high-energy particles. NASA's MARIE (Martian Radiation Environment Experiment) project uses HZETRN to predict the Mars radiation climate based on data collected from the Mars Global Surveyor mission [MARIE].[5] HZETRN is written in Fortran77 for a VAX4000 machine, but is essentially machine and platform independent [HZETRN, Appendix A]. This allows us to adapt HZETRN to parallel machine platform. The current performance of the HZETRN program is apparently unsatisfactory. With a ratio of about 1:3 CPU time needed for analysis vs. duration of data collection, analyzing 50 hours of data requires 18 CPU hours on the current setup [TP-2000-210299].[6] Data have been collected from mid-March 2002 through October 2003. Assuming a similar level of performance, as described in [TP-2000-210299], 4,212 CPU hours, or 175 CPU days, will be needed to analyze about 11,700 hours (487.5 days) of the collected data. HZETRN also underestimates radiation exposure by 15-30% [HZETRN, p. 32]. We need to investigate hardware and software improvements to improve HZETRN's speed of execution, and thus allow a more accurate radiation transport model that can accelerate the MARIE project and ensure a higher level of confidence in the safety of the astronauts.[7]

FLUKA Monte Carlo Radiation Transport Simulation

FLUKA (FLUktuierende KAskede) Monte Carlo technique, developed since 1962, models space radiation transport with much ease and accuracy with 3D capability and produces more specific/detailed results.[8] Similarly, a promising key solution would be to restructure the computation to match the newly developed resource of (1) massively parallel processors (MPP e.g., Cray T3E), (2) multithreading (e.g., Tera Multi-Threaded Architecture MTA), (3) MPI, Open MP or PVM on Symmetric MultiProcessing (SMP) network cluster (e.g., IBM SP-X or workstations), and (4) reconfigurable parallel FPGA computer platforms (e.g., Hypercomputer). Computing with thousands of iterations but being inherently parallel with minimal inter-thread communication in nature, Monte Carlo



RADIATION—Arun Kumar Kadari is completing a master's degree in computer engineering at UHCL. He earned his B.E. in electronics and communications at the Gogle Institute of Technology in India.



COMPUTERS—Shilpa Kodali earned her B.Tech degree in electronics and communications at the J.N.T. University in India; she is currently pursuing the M.S. in computer engineering at UHCL.

research methodology is capable of producing near perfect parallel speedup and cost efficiency shown in such similar applications as photon, charge, or magnetic transport.[9]

***Radiation Impact*—Dual-Use Energy**

As earth's ozone depletion continues, space radiation study could lead to dual-use countermeasures that will, in turn, protect human health from radiation and aging effects, in general, such as treatment to slow cataract development. Other evolving critical medical cures are being effected through proton cancer radiation treatment. With the help of computer architects, scientists will be able to produce better radiation shielding to make nuclear energy safer and more acceptable. This effort will, in turn, uncover the unlimited resources of peaceful nuclear energy that can reduce world oil conflict and global warming. With expertise in high-performance and parallel computing, university and NASA-JSC researchers are devoted to protecting our astronauts and space gear to ensure the success of our future space missions.

***Approach*—High-Performance/Parallel Space Radiation Transport Code Preliminary Investigation for Improvement**

Our study focuses on the radiation transport computation model describing the atomic and nuclear reaction processes that alter GCR in their passage through Martian atmosphere, materiel, and tissue. The current code solves the Botzmann equation using straight-ahead and continuous slowing down approximation to calculate particle fluxes.[4] A preliminary study to restructure current space radiation HZTRN computation suggests the following performance procedures:

- Research a list of prioritized objectives of NASA radiation improvements.
- Study various space radiation models and their mode of execution.
- Analyze every system level of the current space radiation transport computation.
- Remove overhead considering the objectives of improvement in each system level.
- Select domain to partition the space radiation computation for parallel execution.
- Recommend prioritized ways to restructure the space radiation code.
- Suggest a matching parallel computer platform for the restructured code.
- Find ways to evaluate the performance improvement of the proposed changes

To Provide the speed and accuracy needed for achieving NASA's goal in radiation study, reseachers need to complete the following tasks:

- Determine errors induced by fragmentation cross-section uncertainties in calculated particle spectra behind shielding.
- Identify those cross sections that must be determined more accurately.
- Determine remaining deficiencies of the HETC, FLUKA,

and HZETRN codes.
• Develop plans, schedules and costs to correct deficiencies.
• Incorporate further improvements to the Monte Carlo codes HETC and FLUKA and test them using experimental transport data.

Preliminary Results—High-Performance HZETRN

High-Performance HZETRN—HZETRN models the path of space radiation particles by solving the Boltzmann equation for the energy of a particle as it passes through various mediums such as Mars' atmosphere or water shielding. Finding this solution requires integration and interpolation. The current method of interpolation is Lagrange 3rd order. We can pre-compute the intermediate steps of the Lagrange method and store them in a table for reference rather than calculating them each time. Newton's divided difference method yields good results when working with table data.

Depending on the application, other interpolation methods can also be evaluated for accuracy and speed. Integration is done by compound Simpson's with the midpoint interpolated again by Lagrange 3rd order [HZETRN, Appendix A]. This method of integration is a good tradeoff between speed and accuracy. Upon receipt of the HZETRN code, we will also analyze the code itself and will do a critical code execution analysis to find those sections of code that execute the most often (frequently) in order to find other numerical methods or functions that can be improved in accuracy and speed. Adapting HZETRN to parallel platform is also promising by distributing the workload by particles/types.

Language/Data Structure Options Explored—We could also upgrade the code to C++ or Fortran90. There is concern about using C++ in that "C math libraries are slower than the FORTRAN math libraries, except that a C++ wrapper is possibly acceptable by NASA, if it turns out to be warranted or needed," according to Dr. Singleterry of NASA Langley. Fortran90 is a version of Fortran that has been enhanced with emphasis on modernizing the language with features like dynamic memory allocation, more control structures, and operator overloading. Fortran90 is completely backwards compatible with Fortran77 for a smooth upgrade. We can improve the accuracy of HZETRN by updating the code with a simple improvement to increase the number of significant digits in two of the input data files. ATOMIC.DAT and NUCLEAR.DAT both have variables with only three significant digits in order to be compatible with generated data files [HZETRN, p.36].

Space Radiation Accuracy Saves Mission Cost—The high-charge-and-energy transport (HZETRN) model approximates the paths of high-Z and high-energy particles through space. It is used to model the effects and interaction of radiation with various shielding materials. These data are used to help determine the types of shielding necessary to protect astronauts and equipment during the missions to Mars. Any error in the method must be shown and compensated for in the physical shielding.

If the accuracy of the HZETRN code can be improved, overestimation of shielding can be reduced and the weight of the shielding can be reduced at a savings both in cost and in the initial construction since every pound counts on a space mission, especially a long-term mission to Mars. Improved radiation accuracy reduces excessive compensating weight of materiel, thus cutting mission costs.

COMPUTER BOARD—With a B.S. in computer engineering from Texas A&M University, Travis Gilbert continues his studies as a master's student in computer engineering at UHCL.

Speedup Interpolation/Integration—Improved accuracy alone is not enough. The calculation must be done in a timely manner so that the results can actually be used. It does no good to improve accuracy if the results take too long to compute. As mentioned previously, the HZETRN project relies heavily on interpolation and integration. In fact, the integration routine incorporates interpolation. Therefore, if interpolation can be improved, both routines will execute faster and if both can be improved, the code as a whole will execute even faster. Because the HZETRN code uses 3rd order Lagrange interpolation and compound Simpson's method for integration, we are currently attempting to implement both in an FPGA format. Integration will be accomplished by taking one interval and splitting it into two regions, i.e., by interpolating two extra points in addition to the three points given. Parallel routines are also worth trying, e.g., Clarke method and Optimal interpolation for parallel interpolation, as well as Dynamic synchronous and Adaptive algorithm for parallel integration.

HZTRN Experience—Recently, we corresponded with Dr. Cucinotta who informed us that we could run the HZETRN code from the SIREST (<http://sirest.larc.nasa.gov>) system.

We ran several test jobs and found that the TransportMARS application calculates the particle fluxes in a given environment on Mars. The application took 5 hours, 16 minutes, and 47 seconds to process the data from March 1, 1990 to March 7, 1990. (The process started at 14:46:30, Aug 23, 2004; ended 20:03:17, Aug 23, 2004). Without access to the computer itself, we cannot know how much CPU time this represents. The output is odd as well; it does not give a timeline and then the flux for each type of particle over that timeline; it gives a total particle flux over the whole time period. Because of NASA 's new security procedure, we are currently working with LaRC to obtain the actual code for analysis.

Conclusion—Safer/Cheaper/Sooner Mission

We performed a study on the current execution mode or platform for NASA space radiation methods to verify the needs and to propose several options of high-performance and parallel improvement that will bring us to Mars sooner, more economically, and more safely. The study of the feasibility of applying parallel technique to enhance both HZETRN and the FLUKA Monte Carlo radiation transport analysis/simulation code used by NASA scientists will greatly enhance space radiation study, which can also prove vital in studies of safe nuclear energy, anti-aging processes, and cancer treatment. This research can bring about health and peace through new technology advancements.

Personnel

Professor Liwen Shih teaches High-Performance Computer Architecture, Machine Intelligence and Parallel Processing. Dr. Shih and her students successfully improved the performance of Scientific/Image modeling, including the speedup of Medical Image Texture Analysis from 8 days/image CPU time on a VAX Micro 3400 to 40 minutes/image on TMC CM5, and to within 15 seconds/image on a PC platform. They expect to apply their high-performance computing expertise to projected space expeditions to the moon and Mars.

Acknowledgments

Dr. Francis A. Cucinotta of NASA-JSC informed us about feasibility of running the HZETRN code from the SIREST (<http://sirest.larc.nasa.gov>) system. Two researchers currently work with us and will continue to assist us in obtaining radiation transport algorithms and documentation following the new NASA security guidelines: Dr. Robert C. Singleterry Jr., NASA Aerospace Fellow, Research and Technology Directorate, the Computational Structures & Materials Branch of the NASA Langley Research Center, , and Dr. Premkumar Saganti, Associate Professor in Physics and Research Professor of the NASA Center for Applied Radiation Research (CARR) at Prairie View A&M University and Sr. Research Scientist of Space Radiation Health Project (SRHP) NASA-JSC, on the NASA-JSC MARIE Team. The School of Science and Computer Engineering, UHCL, provides us space and computer needs. Many national supercomputing centers, e.g., the Maui High-Performance Computing Center (MHPCC), will provide us remote access accounts if we need to use a large scaled computer system in future work.

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