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Recent and Planned Developments in the CARI Program

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16. Abstract

CARI-6 is the sixth major release of galactic cosmic radiation (GCR) dose calculation software developed by the U.S. Federal Aviation Administration (FAA). The software is of benefit to the FAA and the public as a tool used by scientists investigating health effects of ionizing radiation in the atmosphere. It provides GCR dose estimates for past flights and also serves as a verified radiation monitoring tool to aid the aviation industry and individuals in their radiation protection programs. Compiled versions of the software are available from the Radiobiology Research Team Website. The source code is available upon request.

CARI-6 is based on the last major revision of the galactic cosmic radiation transport code LUIN (LUIN2000, released in 2000). The last minor variant of LUIN2000 (LUINNCRP) was delivered to the FAA in 2003 and reported effective doses as defined in National Council on Radiation Protection and Measurements Report 116. LUINNCRP was revised to produce dose outputs of ambient dose equivalent (H*(10)) and effective dose as defined in International Commission on Radiological Protection (ICRP) Publication 103, in addition to the release standard of effective dose as defined in ICRP Publication 60. These modifications were needed because ICRP Pub. 103 made ICRP Pub. 60 effective doses obsolete (though still legally the standard in many countries) and H*(10) is a measureable quantity to which instruments are often calibrated, whereas effective dose cannot be measured. Thus, adding H*(10) and the new effective dose was needed to keep CARI-6 up-to-date in terms of dose calculation standards. As another improvement, cutoff rigidities for geomagnetic epoch 2000 are included (previous most recent epoch was 1995).

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ABBREVIATIONS

ASP -------- Active server page
BASIC----- Beginner's All-Purpose Symbolic Instruction Code
CAMI ----- Civil Aerospace Medical Institute
CEM------- Cascade-Exiton Model
DOS ------- Disk operating system
FAA-------- Federal Aviation Administration
GCR------- Galactic cosmic radiation
GUI-------- Graphical user interface
ICRP------- International Commission on Radiological Protection
IGRF ------ International Geophysical Reference Field
ISO -------- International Standards Organization
LAQGSM- Los Alamos Quark-Gluon String Model
MCNPX -- Monte Carlo N-Particle eXtended
MS-DOS-- Microsoft ® DOS
NCRP ----- National Council on Radiation Protection and Measurements
NOAA----- National Oceanic and Atmospheric Administration
NIOSH --- National Institute of Occupational Safety and Health
PC---------- Personal computer

I. BACKGROUND

In-flight exposure to ionizing radiation has been a health concern for passengers and crewmembers since the early days of jet travel, with the U.S. Federal Aviation Administration (FAA) establishing the Radiobiology Research Team at its newly founded Civil Aeromedical Research Institute (now called the Civil Aerospace Medical Institute, i.e., CAMI) to investigate the health effects of ionizing radiation as early as 1961.

The primary source of ionizing radiation exposure of aircrews above altitudes of a few thousand feet is galactic cosmic radiation (GCR) (For more information on in-flight radiation exposure sources see DOT/FAA/AM-11/9).[1] By the late 1980s, it was decided that user-friendly software that would calculate a reasonably accurate flight dose from GCR and run on a personal computer (PC) would be a valuable tool for scientists investigating the health effects of radiation and for radiation monitoring of flight crew members. If it was to be used for estimating career doses of multiple pilots, the software would need to be much faster than the radiation transport codes then in use. Radiation transport codes of the time were much too time consuming to use directly. As an example, with LUIN,[2] one of the fastest atmospheric ionizing radiation transport codes of the time, to calculate the dose rate from GCR at a single point in time and space on a IBM PC with an Intel 80286 processor required over 12 minutes of calculations. Thus calculating a radiation dose for even a short flight route could take hours. The development of the software now called CARI significantly shortened that time.

The CARI program has been through four major revisions since 1991. Originally, the program was called CARRIER, but this was later shortened to CARI. CARRIER was based upon dose rate data compiled by Schaefer.[3] CARI-2 and later versions use databases of LUIN dose rate calculations, with each major revision following a major revision of LUIN. Table 1 lists the major releases of CARI, along with the source used for radiation transport and the year of release. LUIN2000, the basis of CARI-6, is described in Appendix A.

The major release versions of CARI were often altered to suit the needs of specific users (e.g., the U.S. Air Force and the U.S. National Institute of Occupational Safety and Health (NIOSH)). Thus, there were 2 versions of CARI-2 (2 and 2N), 4 versions of CARI-3 (3, 3C, 3N, and 3Q), 3 versions of CARI-4 (4/4EZ, 4Q, 4R), 4 versions of CARI-5 (5, 5E, 5AF, and 5G), and there will be 7 versions of CARI-6 (6, 6HF, 6M, 6P, 6PM, -6W and -WEB).

With each major revision of LUIN, a version of CARI (designated by the -L, for LUIN) was developed incorporating the associated version of LUIN directly into the code. These versions had no need of databases of LUIN results, but required much longer times to calculate flight doses. Because of distribution limitations placed on LUIN by Professor O'Brien, these versions were not distributed without his express permission. The CARI-L programs were used to check the associated database-using programs and included CARI-L94 (CARI-3 series), CARI-L97 (CARI-4 series), CARI-LF (CARI-5 series), and CARI-LF2, -LF3, and -LF4 (CARI-6 series). The most significant change in CARI output is from CARI-4, which calculated equivalent dose to bone marrow and skeletal tissue based on equivalent dose at 5-cm depth in a 30-cm tissue equivalent slab phantom, to CARI-5, which began the practice of incorporating the fluence-to-effective dose conversion factors published by Ferrari, Pelliccioni, and Pillon and summarized in Pelliccioni.[7] These factors are used to calculate effective dose following the recommendations of the International Commission on Radiological Protection (ICRP) as described in Publication 60 and modified slightly in Publication 67.[8,9]

Table 1. Radiation Transport Sources used by CARI major releases

Program	Transport Source	Year Released
CARRIER/CARI	Scheafer, 1971 [3]	1989
CARI-2	LUIN [4]	1991
CARI-3	LUIN94 [5]	1995
CARI-4	LUIN97	1997
CARI-5	LUIN98f	1998
CARI-6	LUIN99/LUIN2000 [6]	2000

II. CARI-6

II.1. Current Variants

CARI-6 calculates the effective dose from galactic cosmic radiation received on flight following the shortest route between the origin and destination airports entered by the user. The route (often referred to as a great circle route) followed is the geodesic calculated by the National Oceanic and Atmospheric Administration's (NOAA's) computer programs INVERSE and FORWARD,[10] which take into account the differences between the shape of the Earth and a perfect sphere. The user also enters the flight profile, which consists of minutes to reach the first en route altitude from lift-off, altitude and minutes spent at each en route altitude, and minutes descending to the destination airport from the last en route altitude. When calculating a dose, the program takes into account the effects of changes in altitude, geographic coordinates, solar activity, and the Earth's magnetic field. Deviations of less than 200 miles from the geodesic route have very little effect on the flight dose.

CARI-6M is a version developed for evaluating military, supersonic, and other flights that do not closely follow a single geodesic and may not start or end at a traditional airport. Instead of time-at altitude data and the origin and destination airports, the user enters a set of waypoints. A geodesic route is followed from each waypoint to the next with a constant rate of altitude change assumed if the waypoints have differing altitudes.

CARI-WEB is a single-flight version of CARI-6 that runs from the Internet as a set of active server (ASP) pages.

CARI-6HF generates a world grid of dose rates at a specific altitude. It was developed at the request of the U.S. Air Force.

CARI-6P and -6PM are is the latest variants of CARI developed for the U.S. National Institute of Occupational Safety and Health (NIOSH) for their ongoing retrospective health studies of working women and provide doses by particle. Effective dose is calculated using both the recommended radiation weighting factors from ICRP Publication 60 and the alternate proton weighting factor recommended in NCRP Report 116.[11] An estimate of whole body absorbed dose is also provided.

II.2. Shortcomings

Despite all the above variants, there are several reasons to modernize CARI-6: 1) to provide an output that meets current standards for calculation of effective dose, 2) incorporate newer geomagnetic data, 3) provide dose outputs of ambient dose equivalent (H*(10)), [12] and 4) update the source code to a more portable language.

CARI-6 incorporates magnetic field data from 1965, 1980, 1990, and 1995.[13-16] Since the development of CARI-6 in 2000, a 1-by-1 degree vertical cutoff rigidity table (required by LUIN) has become available for the International Geophysical Reference Field (IGRF) 2000 magnetic field model.[17] A table for 2010 will be available soon.

In 2007, the ICRP released ICRP Publication 103,[18] which substantially altered the neutron and proton radiation weighting factors used in the calculation of effective dose and also made alterations to the recommended values of the tissue weighting factors, relative to those published in ICRP Publication 60. More recently, ICRP released its new standard phantoms for calculation of effective dose (ICRP Pub. 1.0000110).[19] Also, for dose rate measurements aboard aircraft, in recent years ambient dose equivalent (H*10) has become a widely used standard, because instruments such as tissue equivalent proportional counters can be calibrated to measure such an endpoint accurately (effective dose cannot be measured). Thus, there is a clear need for the inclusion of these dosimetry endpoints if CARI is to avoid obsolescence.

All previously distributed versions of CARI-6 were distributed as 16-bit compiled DOS (Disk Operating System) applications (See Appendix B for more details of CARI-6 design). This is two generations behind the modern 64-bit standard and will not run without third-party 16-bit DOS emulation software on some computers (e.g., Windows Business Vista ® 64-bit).

II.3. CARI-6W

CARI-6W eliminates these shortcomings and serves as a bridge to CARI-7 (see Section III, below). CARI-6W has a recalculated database for each geomagnetic epoch, including the addition of the IGRF2000 data. For each epoch, ICRP Publication 60 and ICRP Publication 103 effective doses, H*(10) ambient dose equivalent, and estimated whole body absorbed dose rates are each available both as a total and as a contribution from any of the following particles: neutrons, photons, electrons, positrons, muons, charged pions, and protons.

The core programming of CARI-6W is Fortran.[20] For users for which security is an issue, such as the U.S. Air Force, there is a requirement to not use third party DOS (There were once many versions of DOS from multiple vendors. Parts of Microsoft's MS-DOS still survive in various versions of Microsoft Windows) emulation software such as DOSBox.[21] In addition, the modernization to Fortran provides a framework for incorporation of a modern graphical user interface (GUI) for CARI, while allowing users to avoid the GUI if they wish. Fortran compilers are readily available for both Microsoft Windows ® operating systems and the vast proprietary and freeware Unix family of operating systems, and unlike the many diverse versions of BASIC, each with its own slightly differing syntax (e.g., QuickBASIC vs. GWBASIC), [22] Fortran is highly standardized, with vendors offering compilers with various non-standard extensions to the language in addition to a fixed core following the International Standards Organization (ISO) standard. Thus, with minor modifications, CARI-6W should be useable on practically any system with sufficient disk space and memory, from laptop to mainframe. The final GUI release version will be based on ASP, with the terminal-driven Fortran program also available to those who cannot or do not wish to run the ASP version.

III. CARI-7 AND BEYOND

One of the primary shortcomings of LUIN is the use of the so called "superposition approximation" for atmospheric transport of heavy ions. In the superposition approximation, once a heavy ion enters the atmosphere it is transported as an equivalent collection of independent protons and neutrons with the same energy per nucleon as the original ion (e.g., an alpha particle with a kinetic energy of 10 GeV/nucleon would be transported as 2 free protons and 2 free neutrons each with 10 GeV kinetic energy).

CARI-7, which is being developed concurrently with CARI-6W, will be the first CARI version not to use LUIN as the primary transport code since its adoption for CARI-2. Instead, doses will be calculated from a database of GCR atmospheric particle fluences calculated using the general purpose Monte Carlo radiation transport program MCNPX [23] (or possibly MCNP6), developed at Los Alamos National Laboratory in the U.S. The advantage of this will be avoidance of the superposition approximation treatment of hadronic showers used by LUIN. Unlike LUIN, use of MCNPX does not require this approximation. The MCNPX code incorporates the LAQGSM and CEM models for transport and break-up of galactic cosmic radiation (GCR) ions.[24,25] The disadvantage of MCNPX is the enormous run time associated with all programs that use Monte Carlo methods to solve radiation transport problems.

Cosmic rays reaching Earth's atmosphere are essentially isotropic at most energies. To model propagation through the atmosphere, numerical or Monte Carlo calculations are needed to account accurately for decay and energy-loss processes, and for the energy dependences of the cross sections and of the primary spectral indices of each ion. The database calculations will likely continue through the first half of 2013 before GCR ion atmospheric fluence tables are complete for all the most numerous elements (light elements up through iron).[26] The CARI-7 databases will then replace the LUIN-based databases and be used to expand the capabilities beyond current outputs based on user needs.

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APPENDIX A

Physics of CARI-6: LUIN2000 (Adapted from O'Brien et al., 2003)

CARI-6 relies on a database obtained by running LUIN at a variety of altitudes, latitudes, longitudes, solar activity conditions, and geomagnetic conditions. Thus, the physics of CARI-6 is the physics of LUIN.

There are variations in the galactic cosmic radiation spectrum at the Earth brought about by scattering in the magnetic fields carried away from the Sun in the solar wind. These variations in the galactic cosmic radiation reaching the atmosphere are modeled by means of a fictitious heliocentric electrostatic potential (the "heliocentric potential"), the magnitude of which is related to the count rate of ground level neutron monitors.[A3,A4,A5]

A.1. Recent Changes

The most recent published descriptions of LUIN are by O'Brien et al.[A4,A5] Significant changes since then include:

(a) Recent vertical cutoff rigidity tables from Shea and Smart (up to 1995).[A1,A6-A8]
(b) Fluence-to-effective dose calculations of Ferrari, et al. [A9-A14]
(c) Use of the shape of the FLUKA neutron spectra calculations as guidance for neutrons between 0.5 and 500 Mev.[A15] Neutron spectra calculations below 0.5 MeV use the spectrum of Hess, et al.,[A16] for guidance.
(d) Revision of the primary cosmic ray spectrum using the data of Gaisser and Stanev.[A17]

LUIN is not a flight code, but gives a detailed picture of the cosmic-ray fluxes, ionization and dose rates at a particular time and place. A version of LUIN2000 that yields answers in both H*(10) and E has been compared quite successfully with the measurements of Schrewe.[A18] The following material from O'Brien et al.[A19] describes how LUIN99/LUIN2000 treats the primary spectrum and the geomagnetic field.

A.2. Composition of Cosmic Rays

The primary cosmic-ray spectrum used in the calculations is divided into three groups:

1. Protons in the hydrogen flux, i.e., the unbound or free protons,
2. Protons in the helium and metals flux, i.e., the bound protons,
3. Neutrons in the helium and metals flux.

Bound protons and neutrons are treated in the superposition approximation, i.e., as separate nucleons in the primary flux $\varphi_i(x, E_B)$. For example, a helium nucleus is treated as four separate nucleons: two protons and two neutrons.

Above 10 GeV/nucleon, LUIN utilizes the Peters representation of the integral cosmic-ray spectrum:[A20]

$$\log\Phi = \left\{a - 0.0495\left[11.9 + \log((1.7 + E)\right]^2\right\} \qquad (1)$$

where Φ is the number of particles with energies greater than E (in GeV) per (m^2 sec sr). The differential spectrum is therefore

$$\log\varphi = \left\{a - 0.0495\left[11.9 + \log(1.7 + E)\right]^2 + \log\left[0.0990(11.9 + \log(1.7 + E))/(1.7 + E)\right]\right\} \qquad (2)$$

where φ is now the flux per (GeV m^2 sec sr) per nucleon. The constant a governs the magnitude and intensity of φ. Solving for a in Eq. 2 results in:

$$\begin{aligned} a = {} & 0.5116423291\ln(1.7 + E) + 0.009336279002\ln(1.7 + E)^2 + 7.009695 \\ & + 0.4342944819\ln\left\{23.25843528(17 + 10E)\varphi/\left[274.0076261 + 10\ln(1.7 + E)\right]\right\} \end{aligned} \qquad (3)$$

LUIN utilizes the measurements of Gaisser and Stanev [A17] for relative particle intensities at 10.6 GeV. These measurements are normalized to the oxygen flux (≡1). The oxygen flux per nucleon at that energy is 3.26 x 10^{-6} per (cm^2 sec sr GeV). The data from reference A17 appear in **Table A1**, along with absolute intensities (column 4) obtained by multiplying the data in column 3 by the oxygen flux. The corresponding neutron and proton fluxes per (cm^2 sec sr) have been calculated and are exhibited in columns 5 and 6. These data give some of the global properties of cosmic rays exhibited in **Table A2**.

The cosmic-ray proton spectra below 10 GeV are represented in LUIN by the equation from Garcia-Muňoz, et al.,[A21]

$$\varphi = 9.9 \times 10^{4} \left[E + 780 \ \exp(-2.5 \times 10^{-4})\right]^{-2.65} \qquad (4)$$

where E is in MeV/nucleon. The flux for the bound protons (or bound neutrons) is obtained by multiplying the result of Eq. 4 by the appropriate flux ratio in **Table A1**. While it is possible to use Peters' model for all energies, it is less accurate by about 20%, in the regions tested, than the two-component model just described.

A.3. Geomagnetic Shielding

A charged particle moving in a magnetic field feels a force at right angles to its direction and to the direction of the field. The motion of the particle normal to the magnetic field is circular and given by

$$p = \left(c/10^{8}\right)B\rho\left|Z\right| =\sim 300B\rho\left|Z\right| \qquad (5)$$

where p is the momentum in eV/c, c is the velocity of light, B is the magnetic field strength perpendicular to the particle trajectory in gauss, ρ is the radius of curvature of the particle in cm, Z is the charge in units of the charge on the electron, and $r = p/\left|Z\right|$ is called the rigidity. A particle entering the Earth's magnetic field must have sufficient momentum so that its radius of curvature will be large enough for it to interact with the Earth's atmosphere if it is to produce atmospheric cosmic rays. That rigidity, a function of the particle's charge, and the zenith and azimuthal angles it makes with the Earth's surface is called the "cutoff" rigidity and is expressed in GV (GeV/c per unit charge). Note that an ion, such as helium, with Z/A = 0.5 will have twice the rigidity of a proton with the same energy per nucleon as it has half the charge per nucleon.

The Earth's magnetic field roughly resembles a magnetic dipole of moment 8.1 x 10^{25} erg/gauss (8.1 x 10^{22} J/tesla) with its center several hundred miles from the center of the Earth and pointing south.[A22] The equation of the trajectory of a charged particle in a dipole field has been solved by Störmer. However, the expansion of the Earth's field in spherical harmonics has higher terms than the dipole, for which there is no solution Smart,[A7] and Smart and Shea[A8,A24] have calculated vertical cutoff rigidities for a number in closed form. Using modern digital computer technology, geomagnetic cutoff rigidities are obtained by brute force numerical integration of cosmic ray trajectories in a high order model of the geomagnetic field such as the models provided by the International Geomagnetic Reference Fields.[A23] Shea et al.,[A6] Shea and of magnetic Epochs using numerical methods. These are effective cutoffs, taking into account the shielding of the solid earth and the penumbra. For CARI-6, vertical cutoff rigidities were calculated using the IGRF 1995 internal geomagnetic field model.

Cutoff rigidities in directions other than vertical are determined by the application of theory. Störmer's equation is solved to give cutoffs as function of zenith and azimuth for a dipole field,[A22]

$$R_c(\lambda,\psi) = 60\left[\left(1 - \sqrt{1 - \cos\psi\cos^3\lambda}\right)/\left(\cos\psi\cos\lambda\right)\right]^2 \qquad (6)$$

where λ is the geomagnetic latitude, and ψ is the angle a cosmic-ray particle makes with a vector pointing west and R_c is the cutoff rigidity in GV. Rösler et al.,[A15] have normalized Eq. 6 to the vertical cutoff given by the Shea-Smart calculations. Thus the details of the moments of the geomagnetic field are carried by the vertical cutoff distribution.

Table A1. Composition of Cosmic Rays at 10.6 GeV

Z*	Element*	F*	Nuclear Flux $(m^{-2}\ sec^{-1}\ sr^{-1})$	Neutron Flux $(cm^{-2}\ sec^{-1}\ sr^{-1})$	Proton Flux $(cm^{-2}\ sec^{-1}\ sr^{-1})$
1	H	730	0.00237980	0	$2.37980\ 10^{-6}$
2	He	34	0.00011084	$2.2168\ 10^{-7}$	$2.2168\ 10^{-7}$
3-5	Li-Be	0.4	$1.304\ 10^{-6}$	$6.4174978\ 10^{-8}$	$5.216\ 10^{-8}$
6-8	C-O	2.20	$7.1720\ 10^{-6}$	$5.0244259\ 10^{-8}$	$5.02040\ 10^{-8}$
9-10	F-Ne	0.3	$9.78\ 10^{-7}$	$9.8629833\ 10^{-9}$	$9.291\ 10^{-9}$
11-12	Na-Mg	0.22	$7.172\ 10^{-7}$	$8.7121045\ 10^{-9}$	$8.2478\ 10^{-9}$
13-14	Al-Si	0.19	$6.194\ 10^{-7}$	$8.6923617\ 10^{-9}$	$8.3619\ 10^{-9}$
15-16	P-S	0.03	$9.78\ 10^{-8}$	$1.5667443\ 10^{-9}$	$1.519\ 10^{-9}$
17-18	Cl-Ar	0.01	$3.26\ 10^{-8}$	$6.585314\ 10^{-10}$	$5.705\ 10^{-10}$
19-20	K-Ca	0.02	$6.52\ 10^{-8}$	$1.3097474\ 10^{-9}$	$1.2714\ 10^{-9}$
21-25	Sc-Mn	0.05	$1.630\ 10^{-7}$	$4.4237730\ 10^{-9}$	$3.7490\ 10^{-9}$
26-28	Fe-Ni	0.12	$3.912\ 10^{-7}$	$1.2058297\ 10^{-8}$	$1.05624\ 10^{-8}$

* Gaisser, T.K., Stanev, T. Cosmic Rays, *European Phys. J. C* 3, 132-137, 1998.

Table A2. Global Properties of Cosmic Rays

	Free Protons (Group 1)	Alpha plus Metals	Bound Protons (Group 2)	Bound Neutrons (Group 3)
Z/A	1	0.496	1	0
Flux ratio	1	0.272	0.134	0.137
a	3.71	3.14	2.84	2.85

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APPENDIX B

Organization of QuickBASIC CARI-6

B.1. Source Codes

CARI-6 consists of a set of Microsoft (tm) QuickBASIC codes with associated databases and the program DIST.EXE. The compiled QuickBASIC codes are:

CARI-6.BAS, 6-DOIT.BAS, 6-CALC.BAS, ONESHOT.BAS, AIRPORT7.BAS,

ADD-FLT.BAS, REINDEX.BAS. DIST.EXE is based on NOAA's programs INVERSE and FORWARD (both available in Fortran), and is used to calculate geodesics and distances between locations).

QuickBASIC programs used as libraries are:

CARI-6.BAS: UTIL-6.BAS, NUPORT3Q.BAS, ENTERDATQ.BAS

6-DOIT.BAS: QUAD-4.BAS, BELT-5.BAS

6-CALC.BAS: QUAD-4.BAS, DOS-UTIL.BAS, BELT-5.BAS

ADD-FLT.BAS: NUPORT3Q.BAS

ONESHOT.BAS: QUAD-4.BAS, DOS-UTIL.BAS, BELT-5.BAS

REINDEX.BAS: DOS-UTIL.BAS

Combined there are 15 unique declared functions and 92 unique declared subroutines.

B.2. General Descriptions of the Main Programs

CARI-6.bas is the master program that the user interfaces with to gain access to the others. It is also where the internal help file is available and where users can change DOS driven printer access options by selection of lpt port for printing (default is lpt1). The user is first shown the title information and the MAIN MENU. Other menus follow based on selection from the MAIN MENU.

6-DOIT handles the processing of flight profiles and calculation of route doses

6-CALC handles the calculation of dose rates at individual locations, based on a user generated input file.

ONESHOT is a reduced version of 6-calc for calculation of the dose rate at a single point in time and space in the atmosphere, driven by user input from the screen.

AIRPORT7 is a library of routines used to add and remove airports from the user entered airport database.

ADD-FLT is used to input flight data.

REINDEX is used to sort the airport databases after each possible instance of their revision.

B.3. General Descriptions of the Minor Programs

BELT-5 is the program that calculates dose rates in the low and mid latitudes, based on geographic location. Anywhere outside the 'beltway' is considered to be a high latitude location and dose rates are calculated with QUAD-4. The latitudinal extent of the beltway varies with longitude.

DOS-UTIL contains various file related Subroutines and functions.

ENTERDATQ provides user data entry related routines.

NUPORT3Q primary user interface for adding airports to the database.

QUAD-4 is the dose rate calculator for high latitude (i.e. outside the beltway) locations. Locations are mapped to different vertical cutoff rigidities. Dose rate is based on vertical cutoff rigidity.

UTIL-6 is another collection of utility subroutines and functions.

The declared functions are: FileExists, Get1stMatch, NextMatch, TRIPDIST, UpMinutes, WhichRecord, Search, ChgDir, ABSearch, YESNO, Rd, GetDefualtDisk, PadIt, Find, and AMISReady.

The declared subroutines are: Addaport, addmvs, admenu, Airportmenu, Badnews, Beeper2, Beeper3, Below900, Bisearch, boxit, boxit2, Buildtables, Calcbig, changeport, city, cityport, code, coldlat, Cruising, DataENTR, data-menu, decode, delay1, DeleteRecord, diskit, displaycodes, displayoption, displayrecord, Elevation, Emptyfile,

Emptyfile(v2), Exec, FindHP, GetCoordinates, Hardcopy, HCoption, HelPotMenus, HiOrLo, Idiotproof, inAMIS, Info, interpolate, latitude, loadfilename, locateAirport, longitude, Makefile, Makefile(v2), MakeShortList, ManageScreen, MiddleAltitudes, MVOption, Nof1, NoMV, OBrien, ODAirports, Onedot, Parker, Parkersbox, Printercommand, qsort, Quicksort, readdata, readdata(v2), RectangleCorners,

Rollcall, screenit, screentest, Selectdatabase, Setup, Shopspecs, ShowBeltData,

showfile, showhelp, sortrecords, spline, spline(v2), SwitchIndex, SwitchIndex(v2), TIMEandALT, TimeandDate, todisk, tooearly, Twixtstartandstop, useinverse, validate3, validate3(v2), viewbig, viewshort, Welcome, WhatAirport, Whereis

Altogether there are about 10,000 lines of uniquely purposed basic code.

APPENDIX C

Sample results for comparison

C.1. Single Locations

Tables C1 and C2 show selected single location output for ICRP 60 effective dose, along with the standard CARI-6 results for the same conditions for a date in 2004. It is evident that differences between the two programs are slight, typically less than 1 percent. The low- and mid-latitude locations are at pre-calculated grid-points in all coordinates but time for both programs, and the differences result purely from the effects of changes in the Earth's magnetic field over time. At the higher latitude locations there is an added source for the differences: above the cosmic-ray knee in CARI-6, the latitude and longitude are used to find vertical cutoff rigidity, which is used as a dose selecting coordinate, and then a dose rate adjustment is applied based on altitude, latitude, and longitude, whereas in CARI-6W latitude and longitude are always used directly, i.e., the low and middle latitude grid of CARI-6 is extended to the poles in -6W.

Table C1. CARI-6 and CARI-6W output for the same set of conditions at high and low altitudes at 60 °E and 60 °W longitude at an atmospheric depth of 75 g/cm^2 (altitude of about 59,500 feet).

Latitude (°N)	Longitude (°E)	Altitude (g/cm^2)	DATE	Heliocentric Potential (MV)	CARI-6W Dose Rate (microSv/hr)	CARI-6 Dose Rate (microSv/hr)
85.0	-60.0	75.0	2004/11/00	800	13.33	13.38
80.0	60.0	75.0	2004/11/00	800	13.33	13.38
75.0	-60.0	75.0	2004/11/00	800	13.33	13.38
70.0	60.0	75.0	2004/11/00	800	13.33	13.38
65.0	-60.0	75.0	2004/11/00	800	13.33	13.38
60.0	60.0	75.0	2004/11/00	800	12.49	12.51
55.0	-60.0	75.0	2004/11/00	800	13.31	13.36
50.0	60.0	75.0	2004/11/00	800	9.10	9.01
45.0	-60.0	75.0	2004/11/00	800	11.87	11.95
40.0	60.0	75.0	2004/11/00	800	6.27	6.26
35.0	-60.0	75.0	2004/11/00	800	8.62	8.82
30.0	60.0	75.0	2004/11/00	800	4.56	4.58
25.0	-60.0	75.0	2004/11/00	800	6.08	6.21
20.0	60.0	75.0	2004/11/00	800	3.82	3.84
15.0	-60.0	75.0	2004/11/00	800	4.89	4.93
10.0	60.0	75.0	2004/11/00	800	3.54	3.55
5.0	-60.0	75.0	2004/11/00	800	4.36	4.38
0.0	0.0	75.0	2004/11/00	800	3.97	4.28
-5.0	60.0	75.0	2004/11/00	800	3.92	3.95
-10.0	-60.0	75.0	2004/11/00	800	4.22	4.22
-15.0	60.0	75.0	2004/11/00	800	4.68	4.71
-20.0	-60.0	75.0	2004/11/00	800	4.52	4.52
-25.0	60.0	75.0	2004/11/00	800	6.10	6.15
-30.0	-60.0	75.0	2004/11/00	800	5.18	5.18
-35.0	60.0	75.0	2004/11/00	800	8.82	8.82
-40.0	-60.0	75.0	2004/11/00	800	6.07	6.00
-45.0	60.0	75.0	2004/11/00	800	11.86	11.93
-50.0	-60.0	75.0	2004/11/00	800	7.33	7.23
-55.0	60.0	75.0	2004/11/00	800	13.25	13.29
-60.0	-60.0	75.0	2004/11/00	800	9.74	9.57
-65.0	60.0	75.0	2004/11/00	800	13.33	13.38
-70.0	-60.0	75.0	2004/11/00	800	12.43	12.32
-75.0	60.0	75.0	2004/11/00	800	13.33	13.38
-80.0	-60.0	75.0	2004/11/00	800	13.32	13.37
-85.0	-60.0	75.0	2004/11/00	800	13.33	13.38

Table C2. CARI-6 and CARI-6W output for the same set of conditions at high and low altitudes at 60 ^{o}E and 60 ^{o}W longitude at an atmospheric depth of 500 g/cm^{2} (altitude of about 18,800 feet).

Latitude (^{o}N)	Longitude (^{o}E)	Atmospheric Depth (g/cm^{2})	DATE	Heliocentric Potential (MV)	CARI-6W Dose Rate (microSv/hr)	CARI-6 Dose Rate (microSv/hr)
85.0	-60.0	500.0	2004/11/00	800	0.834	0.838
80.0	60.0	500.0	2004/11/00	800	0.834	0.838
75.0	-60.0	500.0	2004/11/00	800	0.834	0.838
70.0	60.0	500.0	2004/11/00	800	0.834	0.838
65.0	-60.0	500.0	2004/11/00	800	0.834	0.838
60.0	60.0	500.0	2004/11/00	800	0.822	0.827
55.0	-60.0	500.0	2004/11/00	800	0.833	0.838
50.0	60.0	500.0	2004/11/00	800	0.725	0.733
45.0	-60.0	500.0	2004/11/00	800	0.810	0.815
40.0	60.0	500.0	2004/11/00	800	0.595	0.596
35.0	-60.0	500.0	2004/11/00	800	0.707	0.715
30.0	60.0	500.0	2004/11/00	800	0.491	0.493
25.0	-60.0	500.0	2004/11/00	800	0.582	0.592
20.0	60.0	500.0	2004/11/00	800	0.438	0.439
15.0	-60.0	500.0	2004/11/00	800	0.508	0.511
10.0	60.0	500.0	2004/11/00	800	0.418	0.420
5.0	-60.0	500.0	2004/11/00	800	0.484	0.486
0.0	0.0	500.0	2004/11/00	800	0.461	0.488
-5.0	60.0	500.0	2004/11/00	800	0.443	0.447
-10.0	-60.0	500.0	2004/11/00	800	0.481	0.482
-15.0	60.0	500.0	2004/11/00	800	0.497	0.500
-20.0	-60.0	500.0	2004/11/00	800	0.499	0.500
-25.0	60.0	500.0	2004/11/00	800	0.583	0.587
-30.0	-60.0	500.0	2004/11/00	800	0.532	0.532
-35.0	60.0	500.0	2004/11/00	800	0.713	0.715
-40.0	-60.0	500.0	2004/11/00	800	0.585	0.583
-45.0	60.0	500.0	2004/11/00	800	0.809	0.814
-50.0	-60.0	500.0	2004/11/00	800	0.646	0.643
-55.0	60.0	500.0	2004/11/00	800	0.833	0.837
-60.0	-60.0	500.0	2004/11/00	800	0.749	0.752
-65.0	60.0	500.0	2004/11/00	800	0.834	0.838
-70.0	-60.0	500.0	2004/11/00	800	0.822	0.823
-75.0	60.0	500.0	2004/11/00	800	0.834	0.838
-80.0	-60.0	500.0	2004/11/00	800	0.834	0.838
-85.0	-60.0	500.0	2004/11/00	800	0.834	0.838