# MarsREM:The Mars Energetic Radiation Environment Models

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***Abstract*. The high energy ionising radiation environment in the solar system consists of three main sources: the radiation belts, galactic cosmic rays and solar energetic particles. Future Mars missions potentially carry significant risk from long-term exposure to ionising radiation. The Martian Energetic Radiation Environment Models, MEREM, were developed in order to simulate the Martian radiation environment. The models, eMEREM and dMEREM, respectively engineering and detailed Martian Energetic Radiation Environment Models, are based on the Geant4 and FLUKA radiation transport programs, combined with Mars Climate Database model for the atmosphere. MOLA (Mars Orbiter Laser Altimeter) data and gamma-ray spectrometer data have been used to define surface topology and surface composition (including presence of water), respectively.**

***Keywords*: Mars, Radiation environment, ESA** [1]

## I. Introduction

Under ESA's MarsREM Project, two models have been developed to predict the energetic radiation environment for future Mars missions. The detailed Martian Energetic Radiation Environment Model (dMEREM) uses similar principles as MarsREC and PLANETOCOSMICS to perform a detailed Monte Carlo radiation analysis of part of the planet or its moons. As such it provides a high-fidelity Monte Carlo simulation of the environment (planetary atmosphere and surface) and the physical interaction processes using Geant4. The penalty of such a detailed model is the time taken to perform these calculations. The Engineering Martian Energetic Radiation Environment Model (eMEREM) uses the same modelling approaches adopted for the QARM[6] model, relying instead on a set of pre-computed response functions to calculate the shielding effects of the atmosphere and surface for a range of mono-energetic proton and $\alpha$-particle sources. Whilst dMEREM and eMEREM are capable of operating as standalone applications, a SPENVIS-compatible [1], web-based user interface has also been developed to provide an integrated environment to predict the Martian radiation environment, and greatly simplify the operation of the software. Both dMEREM and eMEREM rely on a Pre-processor to define the atmospheric composition and density profile for Mars. In addition, dMEREM uses the Pre-processor output to specify the surface composition and density of Mars, or Phobos and Deimos. The incident particle spectra can be galactic cosmic ray ions, solar energetic protons and heavier ions, or solar X-ray spectra. These primary environments are defined through a separate module which incorporates the current state-of-the-art GCR and SEP models, and an SEP event database generated under the MarsREM Project. The user is allowed to define which energy ranges are to be generated, within the global energy spectrum provided as input, the default values being 10MeV/nuc and 1 TeV/nuc respectively for ions and other hadrons, and 0.5 keV and 11 keV in the case of X-ray primaries. Mars SAPRE module generates the orbital data-file required by eMEREM for calculating the orbital radiation environment.

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## II. The Physical Environment Characterization

### A. Martian Atmosphere characterisation

The European Mars Climate Database (EMCD) model [2][3] provides an excellent description of Mars atmosphere. It contains data on temperature, wind, density, pressure, radiative heat fluxes, and other parameters, resulting from global circulation model simulations, stored on a 5°x5°, longitude-latitude grid from the surface up to an altitude of approximately 120 km.

### B. Mars Surface Characterisation

The available data characterising Mars soil composition comes both from orbiters and from landers [4][5]. While orbiter data reveal global characteristics of the planet and provide surface mappings, data from landers give in-situ analysis and a local description of the corresponding landing sites. A good understanding of the

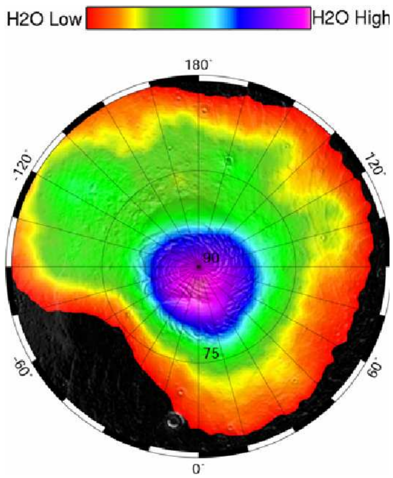


Fig. 1: Map of Martian Hydrogen at the North Pole, July 2004.

available data required an overview of all the missions to Mars. Observations from remote sensing to the different landers measurements suggest that there are compositional differences across the surface of Mars. It was found that the composition of Mars volcanic materials varies from basalt in the ancient southern hemisphere highlands to andesite in the younger northern lowlands. This conclusion is also being confirmed by the different landers measurements. The *line of dichotomy* is the major division of Mars surface and is due to the clear hemispheric asymmetry. It has its most northerly point at about 50° latitude [8]. The southern hemisphere is densely crated and therefore older than the sparsely crated northern hemisphere. This is justified by different meteoritic bombarding periods, or potentially a single *mega-impact* in the northern hemisphere followed by resurfacing by volcanic activity early in the Martian history or itmight have been the site of an early ocean[9].

The presence of water in the Martian atmosphere is already known from atmospheric circulation models (EMCD and Mars-GRAM[10][11]) and already validated by different instruments on board of the multiple missions to the planet. At the surface water can be found mostly in ice-states or in the form of mineral hydration. However, the surface morphology gives several indications of past existence of liquid water at the surface and/or in the underground. Figure 1 shows concentration estimates of equivalent-weight water found in the region of North Pole.

### C. *Phobos and Deimos surface specifications*

The two Martian satellites, Phobos and Deimos are irregularly shaped bodies with rugged limb profiles that indicate fragmentation by impact processes [12]. A density of 2.0 $\mathrm{g/cm^3}$ has been used as default for the Martian satellites in our model. Both satellites are assessed to be about 2 billion years old and appear to have a composition very similar to carbonaceous chondrites (i.e. meteoritic material rich in water and organic content). Since carbonaceous chondrites form in the asteroid belt, it is considered highly probable that both Phobos and Deimos are captured asteroids [12]. The proposed default composition for Phobos and Deimos was based on literature results from meteoritic chondrite [12].

## III. Interfacing data bases: the pre-processor

The MEREM Pre-processor is composed of three interfaces:to EMCD ; to the surface maps extracted from the Gamma Ray Spectrometer, on board of Mars Odyssey [13]; to the Mars-GRAM database. By default it uses EMCD.In order to produce the atmosphere and soil description files, UTC date and time and Location (longitude °E, latitude °N) information are needed. The longitude-latitude pixel accuracy of 5.675° $\times$ 3.75°. By controlling these parameters the user is automatically controlling the space weather conditions. Complete atmosphere and surface description for each specific Mars location, time of day and solar longitude are generated. The latter two are evaluated from the UTC time and coordinates using the Mars24 [14] algorithm, embedded in the pre-processor.

## IV. MarsREM framework

### A. *dMEREM*

dMEREM is a Geant4 application, which calculates the Martian (and Phobos and Deimos) radiation environment through detailed Monte Carlo particle simulations for each set of user input conditions. Since dMEREM incorporates PLANETOCOSMICS, the model allows the user the option of tracking particles within a Mars magnetic field. Previous studies have shown that such effects may be relevant to electron-induced dose, but not as important for protons with energy above 10 MeV. The list of Geant4 physics models used by the dMEREM application allows it simulate in detail the ionization and nuclear interactions of all primary and secondary particles (ions, charged kaons and muons) from 1 TeV/nuc down to 100keV/nuc, and neutrons down to thermal energies. In addition, the full electromagnetic cascade can, if needed, be treated to simulate muons and electrons as well as photons from, e.g. $\pi_0$ decay, nuclear de-excitation, electromagnetic interactions, and X-ray fluorescence. The tool provides output in the form of particle fluence, energy spectra, LET spectra in water and silicon, effective dose and ambient dose equivalent.

The framework developed uses the atmospheric ans soil composition information produced by the pre-processor to build the required geometry (see figure 2). The 3D dMEREM pixel has a square transverse section with default valoes of 300$\times$300 km$^2$, (900 $\times$ 900 km$^2$ if the magnetic field is turned on). The dMEREM default atmosphere is 50 km high, and divided in 20 layers of similar depth (in $\mathrm{g/cm^2}$). A 50 km high atmosphere corresponds approximately to $\approx$ 99% of the total atmospheric depth. If the magnetic field is turned on, an additional 100 km layer is placed on top of the default

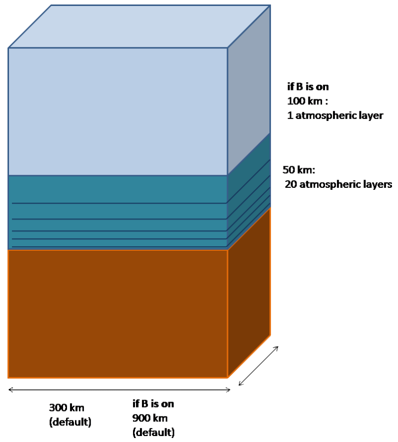


Fig. 2: dMEREM geometry: the 3D pixel.

atmosphere to account for the larger variability on the trajectories of the particles.

In order to optimize the simulation speed, the user can select from one of three other benchmark physics scenarios depending upon the source radiation and output quantities required by the user.

### B. *eMEREM: Engineering Mars Energetic Radiation Environment Model*

Whilst dMEREM is intended to provide an accurate and comprehensive analysis of a localized environment, its reliance on detailed Geant4 simulations prevents easy application to planet-wide radiation analyses. There is a requirement for an engineering model to generate results more rapidly for profiling different locations or orbital conditions. The Engineering Mars Energetic Radiation Environment Model (eMEREM) calculates particle fluence and radiobiological dose based on the same principles used by the QinetiQ Atmospheric Radiation Model (QARM) for Earth's environment. Instead of performing a detailed Monte Carlo radiation simulation for each set of user conditions, eMEREM uses an extensive set of response functions pre-computed using the FLUKA radiation transport code [7]. Each response function defines the environment within the atmosphere and for subsurface conditions, for monoenergetic ions incident at the top of the Martian atmosphere. The environment can then be predicted from the integration of the relevant response functions over the incident particle spectra. However, to help justify this design approach, a series of scoping calculations were performed using the Geant4-based GRAS [21] and MULASSIS [22] tools to better understand the sensitivity of factors such as ground composition/conditions and atmosphere on the observed radiation environment.

## V. Predictions of the Martian Radiation Environment

### A. *Radiation Environment analysis with dMEREM*

The primary spectra used in the simulation correspond to GCR protons in the energy range between 10 MeV/nuc and 100 GeV/nuc, for conditions corresponding to UTC 24Apr2009. The coordinates chosen, 0°N latitude and 0°W longitude, correspond to the region of the Mars Exploring Roving (MER 2) Opportunity landing location. The soil composition for this location is predicted by the dMEREM pre-processor to comprise 5.3% water, 17.9% Fe2O3, 44.6% SiO2, with a density of 1.83 $\mathrm{g/cm^3}$. The atmosphere has a depth of 15.9 $\mathrm{g/cm^2}$ , for the conditions considered.Figure 3 displays the total fluxes of primaries and secondaries (including albedo) arriving on Mars surface. The secondary spectrum is dominated by the albedo, as can be seen in Figure 4. Albedo neutrons dominate for low energy values (below a few tens of keV) and there is a gamma contribution, mostly albedo, between a few tens of keV and 1 MeV. The high energy part of the spectrum is dominated by downward-going protons and neutrons.

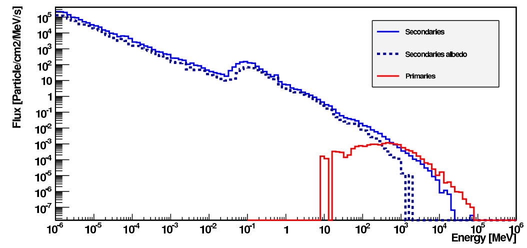


Fig. 3: dMEREM prediction for the total fluxes of primaries (red line) and secondaries (blue line), including albedo (dashed blue line) arriving on Mars surface for a given location and epoch.

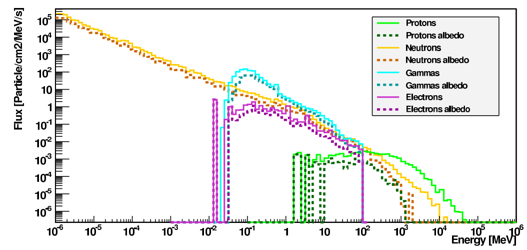


Fig. 4: Full spectrum due to GCR protons on Mars surface, for given location and epoch.

### B. *Radiation Environment analysis with eMEREM*

Ambient dose equivalent maps predicted by eMEREM for the surface of Mars as a result of the combined effects of GCR protons and $\alpha$-particles are displayed in figures 5 and 6 corresponding to solar minimum and maximum, respectively. These show only 15-20% variation in the dose with location. However, the predictions for solar minimum are approximately a factor of 2.2 higher than the solar minimum results. The analysis of De Angelis *et al.* [23]give the dose equivalent predictions from their model for the surface of Mars (located on regolith) as 33.4 Sv/hour and 13.6 Sv/hour for solar minimum and maximum conditions. Therefore, the two models appear to be in good agreement, bearing in mind that the eMEREM data do not yet include the contribution of GCR ions heavier than $\alpha$-particles, and the comparison is not between identical radiological dose quantities. De Angelis et al show a greater difference in the predicted surface neutron flux 100MeV (their predictions varying between 0.8 to 3 neutrons/cm$^2$s across the surface of the planet). Clearly the contributions of heavier GCR ions may explain some of the difference, but this requires further analysis.

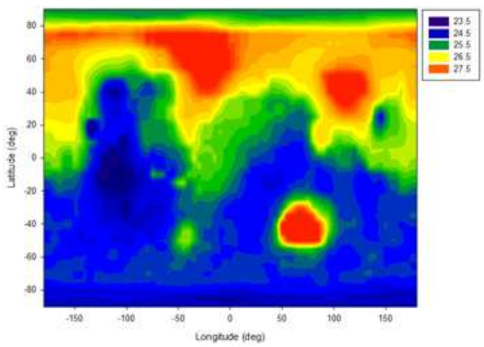


Fig. 5: Ambient dose equivalent at Mars surface as a result of the combined effects of GCR protons and $\alpha$-particles for solar minimum conditions.

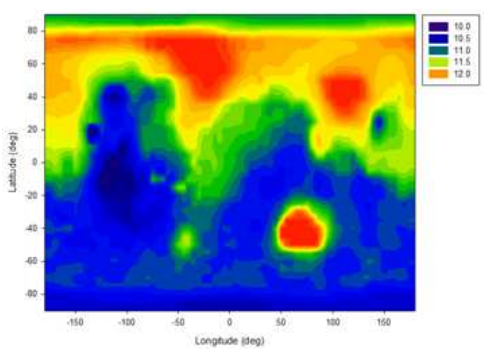


Fig. 6: Ambient dose equivalent at Mars surface as a result of the combined effects of GCR protons and $\alpha$-particles for solar maximum conditions.

Ideally, the eMEREM predictions should be compared with experimental data. However, very few measurements have been made in the vicinity of Mars, one source of data being the Mars Radiation Environment Experiment (MARIE) flown on the Mars Odyssey spacecraft [24]. The results of the analysis of Saganti *et al.* [25] indicate that the average GCR-induced dose measured by the instrument in orbit during August 2003 was 214 Gy/day. Of this, Saganti *et al.* estimate that 56% (120 Gy/day) arise from $\alpha$-particles and lighter galactic cosmic rays. Using eMEREM, the predicted dose for the 400 km altitude orbit of Odyssey is 71 Gy/day from protons and $\alpha$-particles.

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