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COSMOS X as a general purpose air shower simulation tool

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An air shower simulation package COSMOS was born in 1970's and has been continuously developed. A recent major update enables particle tracking not only in the atmosphere but also in arbitrary gas, liquid and solid materials by combining with the EPICS detector simulation package. This paper describes the properties of this extended version of COSMOS, namely COSMOS X. Combination of gas, liquid and solid materials in spherical shells with a common center can be defined as environment. Users can also arbitrary define the electric and magnetic fields. These features allow shower simulations even in the soil, concrete, sea and ice. Also simulations at the Sun and the Mars are possible applications. Flexible input/output control since the previous versions of COSMOS, a set of user hook functions, is also available. In the predefined user functions, information of each particle in transportation can be easily accessed and users can extract information from them. General introduction to COSMOS and new functions of COSMOS X together with some interesting application cases will be presented in this paper.

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1. Introduction

Air shower Monte Carlo simulation code is an important tool in the cosmic-ray physics. In the recent years, precise measurements of air shower particles are required to identify the primary particle type, such as mass number, photons and neutrinos. Especially mass estimation is a hot topic because it is related to the maximum acceleration energy per nucleon and the propagation in the photon and magnetic fields [1]. In the interpretation of air shower observables, mass estimation always suffers from the uncertainty of the hadronic interaction modeling [2] [3] [4]. Thanks to the variety of measurements at the Large Hadron Collider up to $\sqrt{s}$=14 TeV, equivalent to $E_{CR}=10^{17}$ eV, extensive studies in the interaction models are on going both experimentally and theoretically [5]. From the air shower side, precise measurements and joint efforts between the collaborations reveal a so-called *muon puzzle*, where observed number of muons are larger than expected and the discrepancy becomes larger at the highest energy [6].

It is clear that our knowledge on the air shower development is not perfect and the importance of sophisticated air shower MC tools is increasing. Currently CORSIKA [7] is the most popular air shower simulation tool and actively updated for variety of applications and according to the improvements of the interaction models. COSMOS has also a long history since 1970's and also follows the updates of interaction models [8]. It is studied that COSMOS and CORSIKA show good agreements in the basic air shower properties [9]. Because of the importance of air shower simulation tool, the COSMOS development team is formed and the extended COSMOS, COSMOS X, is developed [10]. The goals of the project are to maintain an independent code from CORSIKA, to tackle the problems in the air shower observations and to expand the application of air shower simulations in wider field.

Measurements of cosmic photons and neutrinos are also very hot topics. In the recent observations not only atmosphere but also soil, water and ice are used as absorbers of electromagnetic components and even hadronic components. In the current simulation, shower developments in such non-air materials are calculated separately from the air shower simulation using high-energy physics toolkit like GEANT4 [11]. In such cases, connection of two tools and validity of interaction models at very high energy are concerned. COSMOS X, and also a new version of CORSIKA 8 [12], is designed to track particles in the non-air materials using the high-energy interaction models. COSMOS X will play an important role in the simulations of modern experiments.

2. COSMOS and COSMOS X

2.1 Common features in COSMOS and COSMOS X

The source codes of COSMOS (up to version 9) are available from the website [8]. The codes are written in FORTRAN and can be compiled by the GFortran and the Intel compilers. (GFortran became available since version 9.) Platforms tested are Linux and Mac OS X. Users can simulate air shower developments through a few control files listed below. The relation between these user interfaces and the system functions are illustrated in Fig.1.

- parameter file
- primary file

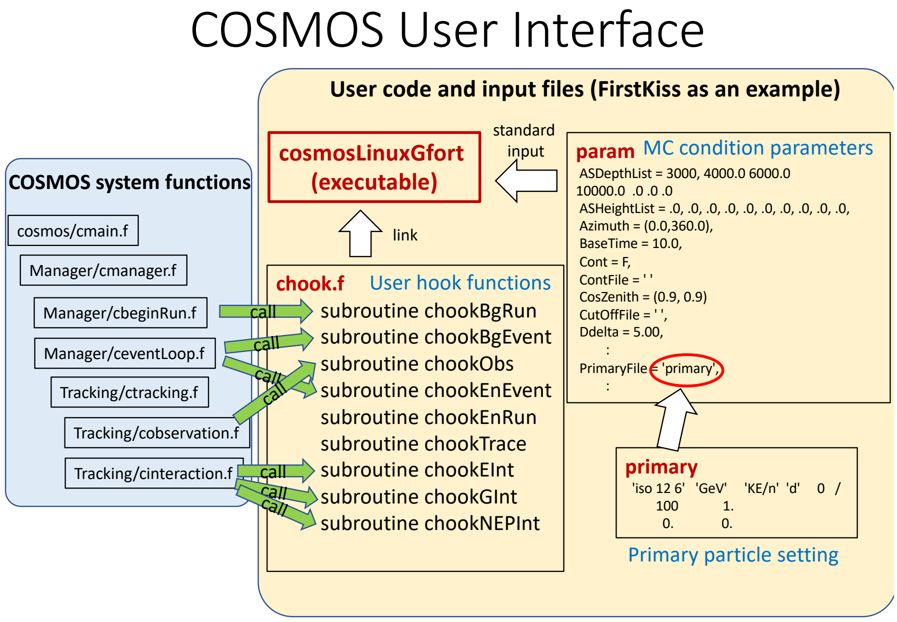

Figure 1: User interfaces of COSMOS system.

- userhook functions

The parameter file (*param*) contains a list of parameters such as observation site (longitude, latitude and altitude), zenith angle range, altitudes of sampling, threshold energies of particle tracking, file name of the primary information, and so on. Primary particles are specified in the primary file (*primary*). The format of the primary file is flexible so that mixed compositions, arbitrary energy spectrum either in integral or differential, either in kinetic energy, energy per nucleon and other units are available. This is convenient to reproduce primaries based on the different experimental results.

The userhook functions are defined in a FORTRAN user function *chook.f*. At several predefined steps in the system functions, the userhook functions are called. This includes the initialization of a simulation (chookBgRun), beginning of each primary injection (chookBgEvent), passage of particles at the predefined altitudes (chookObs) and at the ends of an event (chookEnEvent) and the simulation (chookEnRun). According to the calls, the users can access the information of the particle and handle it as desired in chook.f. Output format, calculation or histogramming of any parameters can be programmed by the users. This sounds somewhat complicated at beginning, but a few simple examples with text output help the users to start simulations.

Introduction of arbitrary functions of electric and magnetic fields in the simulation volume are possible. This allows simulations of particle acceleration in thunder clouds which is a recent important topic [13] [14]. Particle tracking in the geomagnetic field far away from the atmosphere is also available.

2.2 New features in COSMOS X

The most important difference of COSMOS X from the previous COSMOS is a unification with another package EPICS [15]. EPICS was developed to track particles in the materials, similar to GEANT4 but is capable of using high-energy interaction models such as QGSJET [16] and EPOS [17]. Combining two, seamless calculation of air showers in any arbitrary materials become available. To keep a simplicity, the shape of the materials is limited to be spherical shell with a common center. Even within this limitation, a lot of applications are possible.

From COSMOS X, compilation using CMake software becomes available, which reduces the environment dependence. An example code of visualization using ROOT is also prepared as shown in Fig.2.

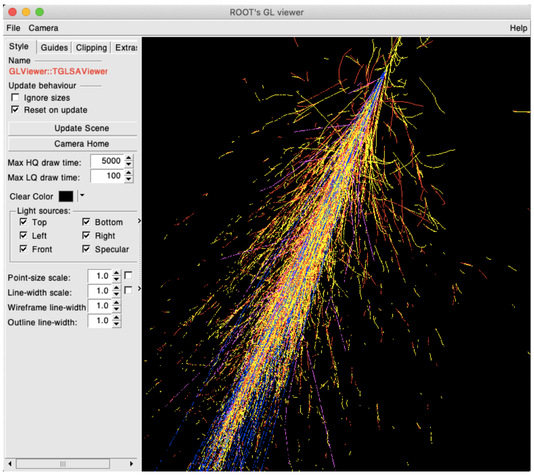

Figure 2: An example of visualization using ROOT.

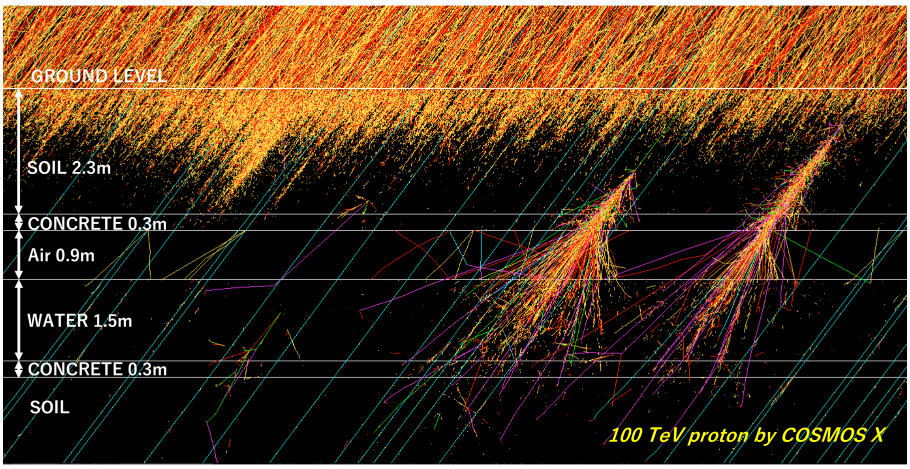

Figure 3: Zoom-in view of a 100 TeV proton shower near the ground. Interactions and tracks in the soil, concrete and water are seamlessly simulated from the air shower.

2.3 Some applications

First useful example of COSMOS X is a calculation in soil and underground water as realized in the Tibet ASγ experiment for the muon detector (MD) [18]. Figure 3 shows a side view of a 100 TeV proton shower above and below the ground. Here, the soil, concrete, air and water layers are defined as spherical shells with a common center at the center of the Earth and with radii similar to the radius of the Earth. This configuration allows essentially flat and parallel layers of various materials. In Fig.3 most of the electromagnetic components shown in red and orange lines are absorbed in the 2.3 m thick soil layer, however, only some hard components and muons (blue) can penetrate deep into the water layer.

Some other interesting applications are summarized in Fig.4. Figure 4 (Left) is an air shower entering in a 6 floor building. Sub-shower developments in the concrete floors are visible. Middle panel shows a trajectory of a charged particle trapped in the geomagnetic field without interaction. Right panel is an air shower developed in the solar atmosphere with a toy model of the solar magnetic field. A 10 TeV proton enters from left-top directing to the photosphere located at the bottom. Because of a low density over a wide scale height, many secondary particles escape along the magnetic field before developing a cascade shower. To understand the recent observations of gamma-ray variability at GeV region [20] caused by interactions between the galactic cosmic rays and the solar atmosphere, update of the pioneering calculations at such condition [19] is required with MC technic and realistic magnetic field configurations.

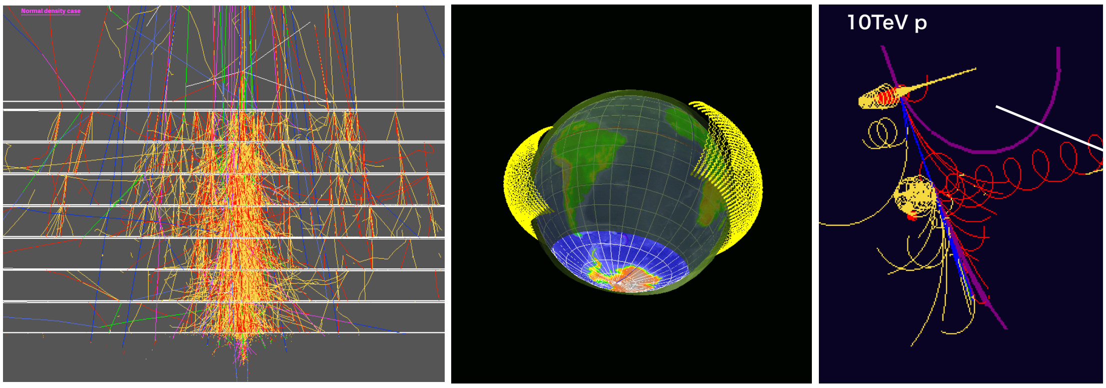

Figure 4: Some interesting applications of COSMOS X. Left) An air shower in a building with concrete floors. Middle) Particle tracking in the geomagnetic field. Right) Particle tracking in a toy solar atmosphere.

3. Summary

Because of the recent developments of precision air shower experiments and hadronic interaction modelings, the importance of air shower simulation is increasing. Furthermore, in the recent cosmic-ray experiments, the target materials are not limited in the atmosphere but also soil, water, ice and so on are used in the particle identifications. Targets of air shower development are not necessarily in the Earth but also the Sun and other planets are interesting applications. Under such situation, the development of COSMOS X has started based on the existing COSMOS and EPICS codes.

In the development phase, not all useful functions are migrated to COSMOS X yet. However, basic functions are already tested and useful sample codes are ready for the users. A β version is available at web page [10]. Any trial and feedback to the development team are welcome.

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