Recent Additions to the Extensive Air Shower Simulation Code CORSIKA*

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Abstract

The Monte Carlo program CORSIKA simulates the evolution of extensive air showers in the atmosphere initiated by photons, hadrons or nuclei. Besides the already available 5 models DPMJET, HDPM, QGSJET, SIBYLL, and VENUS describing hadronic interactions at high energies we have added the new model NEXUS. Based on the universality hypothesis of the behavior of high energy interactions, NEXUS in its unified approach combines Gribov-Regge theory and perturbative QCD, including Reggeons, soft Pomerons, semi-hard Pomerons as a QCD-evolution of soft Pomerons, and parton-parton scattering.

A further CORSIKA addition is the 'curved' option which allows a correct treatment of showers incident at large zenith angles $> 70^o$. At those angles a deviation from a planar atmosphere caused by the curvature of the Earth's surface must be taken into account. The new extensions and features of CORSIKA are described.

1 Introduction:

The extensive air shower simulation code CORSIKA (**CO**smic **R**ay **SI**mulation for **KA**SCADE) (Heck et al., 1998) originally was developed to understand and interpret the data measured by the KASCADE experiment (Klages et al., 1997; Kampert et al., 1999). By various additions and extensions for, e.g. neutrinos, Cherenkov radiation, highest energies including Landau-Pomeranchuk-Migdal effect and thin sampling, various computing systems etc. (Heck & KASCADE collaboration, 1997) during the last decade CORSIKA has become a multi-purpose working horse for cosmic ray investigations and is now employed by ≈ 200 users in more than 60 laboratories around the world.

2 The NEXUS Interaction Model:

NEXUS (Drescher et al. 1998) is the result of a common effort of the authors of VENUS (Werner, 1993) and QGSJET (Kalmykov & Ostapchenko, 1993). It combines basic treatments of these two codes in a new approach, creating a new generation interaction model. Many additions and new ideas are included which

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	DPMJET	HDPM	NEXUS	QGSJET	SIBYLL	VENUS
Gribov-Regge	+		+	+		+
Minijets	+		+	+	+	
Sec. Interactions			+			+
N-N Interaction	+		+	+		+
Superposition		+			+	
Max. Energy (GeV)	$> 10^{11}$	10^8	2×10^8	$> 10^{11}$	$> 10^{11}$	2×10^7
Memory (Mbyte)	52	8	123	10	9	21
CPU time/shower (min)	2.6	1.0	35	1.0	0.75	4.5

Table 1: Basic features of hadronic interaction models. CPU times for: p primary, $E_0 = 10^{15}\ eV$, vertical, $E_h \geq 0.3\ GeV$, $E_\mu \geq 0.3\ GeV$, $110\ m$ a.s.l., NKG option, DEC 3000/600 AXP ($175\ MHz$); NEXUS values preliminary.

should allow an extension for an appropriate and reliable description of hadronic interactions also at highest energies with $E_{lab} > 10^{20}\ eV$.

Basically, NEXUS starts from the universality hypothesis (Drescher et al., 1999) saying that *the behavior of high-energy interactions is universal*. The nucleon-nucleon interaction for instance, is deduced from the lepton-nucleon scattering with photon exchange, ordering the ladder of partons emitted from the nucleon according increasing virtuality such that the parton with highest virtuality comes closest to the photon. In the nucleon-nucleon interaction the ladder is ordered to have the partons with highest virtuality in the middle, such as two lepton-nucleon ladders fused at their photon side. This ladder representing the semihard Pomeron can be treated by QCD evolution and is coupled to the nucleon by a soft Pomeron or a Reggeon, as described in (Werner et al., 1997). Parameters for the string fragmentation are obtained from e^+e^--data employing the 'kinky string' method. By this approach the modeling of the complicated mechanism of hadron-hadron interaction is decomposed into separate 'building blocks' which are deduced from simpler systems like the deep inelastic lepton-nucleon scattering. Tab. 1 compiles the basic features of the hadronic interaction models. NEXUS combines the advantages of VENUS with its detailed treatment of N-N interactions respecting possible interactions of the produced secondaries, and the QGSJET program treating the hard processes. However, the improvements go on the expenses of intense CPU resources.

Preliminary tests of extensive air shower simulations with CORSIKA/NEXUS showed the need for small final corrections in the NEXUS programming to obtain reasonable agreement with experimental data in a quality which resembles the parent programs VENUS and QGSJET as compared in (Knapp, Heck & Schatz, 1996; Knapp, 1998).

3 'Curved' Option:

In the CORSIKA standard version a plane atmosphere is assumed and the penetrated thickness increases with $1/\cos\theta$. This limits simulations to zenith angles $\theta < 70^o$. Above this value the difference between a flat atmosphere and a true spherical atmosphere becomes more and more important and at $\theta = 90^o$ the thickness of a planar atmosphere reaches infinity, compared with $\approx 37000\ g/cm^2$ for the true spherical case. Therefore, for large zenith angles $\theta > 70^o$ the Earth's curvature must be taken into account.

To avoid lengthy formulas for a treatment in a spherical coordinate system with corresponding long CPU times the description of particle transport in a Cartesian coordinate system is kept, but the horizontal step size is limited to $< 20\ km$. Longer transport distances are divided into appropriate segments to be treated in a local flat atmosphere. After each traversed segment the particle coordinates are transferred into the next local Cartesian coordinate system with its vertical axis pointing to the middle of Earth. Thus the curved Earth's surface is approximated piece by piece by flat segments with limited horizontal extension. A similar treatment has been described by (Sciutto, 1998).

A comparison of simulations performed at $\theta = 70^o$ for hadrons and muons with the 'standard' and with the 'curved' version revealed an increase of CPU time by $\approx 30\%$. The validity of the coordinate transformations at the segment boundaries has been checked by the deviation of the particle trace from the detector center after penetrating the complete atmosphere without interaction and without magnetic deflection, impinging on the detector with $\theta = 89^o$. This needs a horizontal transport over a distance of $\approx 1100\ km$ corresponding with a movement over 10^o degrees along an Earth's meridian. The test revealed a missing of the detector center by $< .0003\ mm$ caused by rounding errors in double precision calculations.

4 Other Modifications and Additions:

4.1 Inelastic cross-sections for QGSJET: Motivated by discrepancies between the observed hadron rates and CORSIKA/QGSJET simulations (Risse et al., 1999) the QGSJET code (Kalmykov & Ostapchenko, 1993) has been modified (Ostapchenko, 1998) to increase the inelastic hadron-proton cross-sections within the error bars of collider data. Following a μ trigger with $n_\mu \geq 9$ in the KASCADE calorimeter fewer hadrons with $E_{had} > 100\ GeV$ are observed than predicted by the simulations. In the QGSJET modifications the cross-section values at $E_{lab} = 100\ GeV$ are kept largely unchanged, but with slightly steeper slopes they arrive at 5% higher values at $E_{lab} = 1\ PeV$. With these modified cross-sections the simulated hadron rates are lowered by $\approx 22\%$, but they are still higher than the rates observed in the calorimeter. A further slight improvement of QGSJET is attained by omitting the restriction of diffractive collisions to diffractive masses $m_D < 5\ GeV$. This leads to a minor increase of average inelasticity. The hadron rates predicted by CORSIKA simulations employing other interaction models exceed the CORSIKA/QGSJET prognosis clearly (Risse et al., 1999).

4.2 Improved EGS4 coding: Double precision calculation is now used throughout in the EGS4 package (except for EGS4 cross-section files). By suitable means the large ($\approx 100\ \%$) fluctuations in the probability for direct $\gamma \rightarrow \mu^+\mu^-$-pair formation - resulting from inadequate numerical representation in the cross-section file - could be reduced by a factor of 10. As side effect, the photonuclear probability became a much more smoothed function of energy. The trigonometric functions gained by interpolation from precalculated tables with limited precision ($\approx 10^{-5}$) are now replaced by intrinsic double precision functions improving the angular precision by several orders of magnitude on the expenses of $\approx\ 30\%$ enlarged computing times.

4.3 Atmospheres: To adapt to the atmospheric conditions at various geographic places and at various seasons, sets of atmosphere parameters are available for: U.S. standard, 8 seasonal conditions as measured for middle Europe, tropical (annual average), mid-latitude summer and winter, sub-arctic summer and winter, and South pole at 4 seasons. Additional atmospheres may be introduced by the user in tabular form of altitude dependent densities and mass overlays. For some of the atmospheres also the refractive index for precise correction of Cherenkov photon ray tracing is available (Bernlöhr, 1998), as it is needed for imaging atmospheric Cherenkov telescopes with observation at large zenith angles.

4.4 Energy Balance: Detailed tables are added to the CORSIKA output giving the energy contained within the various particle species (γ, e^+, e^-, μ^+, μ^-, hadrons, all charged particles, and nuclei) as a function of atmospheric thickness in intervals specified by the user. A second table gives the energy deposit within each interval by ionization and by energy or angular cuts, listed separately for γ, $e^\pm$, $\mu^\pm$, and hadrons. Also the energy carried away by neutrinos is counted. The longitudinal sum of these deposits completes the energy balance.

4.5 Imaging Atmospheric Cherenkov Telescopes: A set of **C**-routines (Bernlöhr, 1999) has been implemented to treat the Cherenkov photons as registered by imaging atmospheric Cherenkov telescopes.

5 Program Distribution:

The CORSIKA program files including an up-to-date version of the User's Guide (Knapp & Heck, 1993) are available via anonymous ftp from ftp-ik3.fzk.de (restricted access). Interested users should contact the corresponding author. Further details are given on the web page **http://www-ik3.fzk.de/~heck/corsika/** .The next release of CORSIKA comprising these additions and improvements is planned for end of 1999.

Acknowledgments:

We thank K. Werner for the permission to use NEXUS, for his assistance in coupling it with CORSIKA and for many helpful discussions. Special thanks go to S. Ostapchenko for preparing the modified cross-sections of QGSJET. The contribution of South pole atmosphere parameters by D. Chirkin is acknowledged as well as the EGS4 cross-section file improvement by P. Steffen. We would like to thank all colleagues, who have contributed to the development of CORSIKA by reporting detected errors, suggestions and experiences.

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