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Solar-Terrestrial Models and Application Software

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CONTENTS

Introduction 1- 1

Ionosphere 2- 1

General Models

International Reference Ionosphere 2- 3

Electron Density Models

Chiu Ionospheric Model 2- 4
Bent Ionospheric Model 2- 5
Penn State Mk III Model 2- 6
SLIM Model 2- 7
FAIM Model 2- 7

F2-Peak Models and Applications

CCIR *foF2* and *M(3000)F2* Model Maps 2- 8
URSI *foF2* Model Maps 2- 9
ISS-b *foF2* Maps 2-10
MINIMUF/QSTMUF Model 2-11
IONCAP Model 2-11

Electron Temperature Models

Density Dependent Electron Temperature Model 2-12
AEROS Electron Temperature Model 2-12
AE/ISIS Electron Temperature Models 2-13

Ion Composition and Drift Models

DY Ion Composition Model 2-14
ISR Ion Drift Model 2-15
St. Santin Ion Drift Model 2-15

Electric Field

Polar Cap Potential Drop Model 2-16
Volland Electric Field Model 2-16
Heelis Electric Convection Field Model 2-17
Utah Electric Convection Field Model 2-17
IZMIR Electric Field Model 2-18
Millstone Hill Electric Field Model 2-19
Heppner-Maynard-Rich Electric Field Model 2-20

Auroral Precipitation and Conductivity Models

Rice Electron Precipitation Model 2-21
AFGL Electron Precipitation Model 2-22
AFGL Ion Precipitation Model 2-22

Miscellaneous Auroral Models

Auroral Oval Representation 2-23
Auroral Absorption Model 2-23

Atmosphere 3- 1

Density and Temperature Models

U.S. Standard Atmosphere 3- 3
Jacchia Reference Atmosphere 3- 4
Atmospheric Handbook 3- 4
COSPAR International Reference Atmosphere: 0 km to 120 km 3- 5
COSPAR International Reference Atmosphere: Thermosphere 3- 6
MSIS Model 3- 7

Wind Models (Thermosphere)

Horizontal Wind Model (HWM) 3- 8

Magnetosphere 4- 1

Magnetic Field Models (Main Field Only)

Summary Table 4- 3
Jensen-Cain Model Coefficients 4- 4
GSFC (9/65) Model Coefficients 4- 4
GSFC (12/66) Model Coefficients 4- 5
POGO (3/68) Model Coefficients 4- 5
POGO (10/68) Model Coefficients 4- 6
POGO (8/69) Model Coefficients 4- 6
POGO (8/71) Model Coefficients 4- 7
AWC (75) Model Coefficients 4- 8
IGS (75) Model Coefficients 4- 8
MGST (6/80) Model Coefficients 4- 9
MGST (4/81) Model Coefficients 4- 9
GSFC (9/80) Field Model 4-10
GSFC (12/83) Field Model 4-10
USGS Model Coefficients for Continental U.S. and Hawaii 4-11
IGRF 1945-1980 Model Coefficients 4-11
GSFC (11/87) Model Coefficients 4-12

Magnetic Field Models (With External Sources)

MDTILT Magnetic Field Model 4-13
Olson-Pfitzer Field Model 4-13
Mead-Fairfield Field Model 4-14
Geotail Field Model 4-14
Tsyganenko Magnetic Field Model (Related Software) 4-15

Magnetic Field Models (Related Software)

FIELD/FIELDG 4-16
INVAR/NEWMAG 4-17
ALLMAG/INVARA/LINTRA 4-18
FELDG/SHELLG/INTELG 4-19
NEWBL 4-20
TRAJLST 4-20

BILCAL/IGRF 4-21

Trapped Particle Models and Related Software

AE/AP Trapped Particle Flux Maps 4-22
MODEL Program 4-25
RADBELT 4-26
FLOUT Transformation 4-26
ORP/ORB Package 4-27
SOFIP 4-28
SHIELDOSE 4-28
Spacecraft Radiation Exposure Studies 4-29

Sun and Interplanetary Space 5- 1

Solar Reference Spectra

IR Spectrum of Sun and Earth Atmosphere 5- 3
Revised SERF2 Solar EUV Flux model 5- 3
EUV Reference Spectrum 74113 .... 5- 4

Solar Flare Protons

SOLPRO Model 5- 5
JPL Proton Model 5- 6

Cosmic Rays and Related Software

CREME Programs 5- 7
Spacecraft Anomaly Data Base 5- 8

Planets 6- 1

Venus

PV Thermospheric Model 6- 3
PV Ionospheric Model 6- 3
Venus International Reference Atmosphere 6- 4

Solar-Terrestrial Indices 7- 1

Definition of Indices

Sunspot Number 7- 3
Ottawa 10.7 cm (2800 MHz) Solar Radio Flux 7- 3
I_{F2}, *IG* Ionospheric Indices 7- 3
Correlation Among Monthly Solar Activity Indices 7- 4
Kp Index 7- 4
ap, *Ap*, *Cp*, and *C9* Indices 7- 5
Dst Index 7- 6
AE, *AU*, *AL*, *AO* Indices 7- 6
Summary List of Geomagnetic Indices 7- 7

Availability of Indices

Solar-Terrestrial Indices on Diskette and Tape 7- 8
Solar-Terrestrial Indices on CD-ROM 7- 9
Interplanetary Plasma and Field Parameters (OMNI Tape) 7-10

Solar-Terrestrial Indices in Journals and Reports 7-11

Appendices 8- 1

Appendix A: Solar-Terrestrial Coordinates and Coordinate Systems 8- 3
Appendix B: Coordinate Conversion Software 8- 9
Appendix C: Cosmic: PC Software 8-11
Appendix D: Table of NSSDC IDs Included in This Report 8-13

INTRODUCTION

This document lists and describes the empirical models related to solar-terrestrial sciences which are available in the form of computer programs. Also included are programs that use one or more of these models for application specific purposes. The entries are grouped according to the region of the solar-terrestrial environment to which they belong and according to the parameter which they describe. Regions considered in this document include the ionosphere, atmosphere, magnetosphere, planets, interplanetary space, and heliosphere. The last section provides information on the accessibility of solar and magnetic indices. These indices are needed for solar-terrestrial models to specify the magnetic and solar activity conditions.

The majority of these software packages are maintained and distributed by the National Space Science Data Center (NSSDC). All programs held at NSSDC are written in FORTRAN and have been tested on an IBM or VAX mainframe computer. They are sent to requesters on magnetic tape or on line on the Space Physics Analysis Network (SPAN). Several of the programs have been revised for use on IBM compatible personal computers (PCs) and are sent out on 5¼ or 3½ inch diskettes (floppy disk). In most cases, the model software does not require a PC with math co-processor.

Several frequently requested models have been outfitted with an interactive front-end which allows online specification of input parameters and output options. These models are the International Reference Ionosphere (IRI), the Mass Spectrometer and Incoherent Scatter (MSIS) neutral thermosphere model, the International Geomagnetic Reference Field (IGRF), and the AE-8/AP-8 models of the trapped particle fluxes in Earth's radiation belts. All four of these models can also be accessed and executed on line on the NSSDC Online Data and Information Service (NODIS) account: From a SPAN node, SET HOST NSSDCA, then USERNAME = NODIS; then follow the prompts and menus.

This handbook continues the series of catalogs in which NSSDC presents its data set holdings. All entries in this document are part of the NSSDC Supplementary Data File (NSDF) system, which contains all NSSDC data not associated with individual spacecraft instruments. All NSDF items are listed in the periodically published NSSDC Data Listing (the most recent edition is NSSDC 90-06, 1990).

The software packages on tape or diskette and documentation on microfiche can be ordered from—

- For U.S. researchers:

  National Space Science Data Center
  Code 933.4
  Goddard Space Flight Center
  Greenbelt, Maryland 20771
  Telephone: (301) 286-6695
  Telex: 89675 NASCOM GBLT
  TWX: 7108289716
  FAX: (301) 286-4952
  SPAN: NSSDC::REQUEST

- For researchers residing outside the U.S.:

  World Data Center A for Rockets and Satellites
  Code 930.2
  (Address same as above.)

NSSDC invites members of the scientific community who would like to share their models or application software either to submit the programs and supporting documentation to the data center or to provide a sufficient description to NSSDC for entry into our information system and subsequent display to interested scientists. Periodical updates of this models catalog are anticipated. Comments and suggestions concerning the content and format of the individual entries are welcome.

We hope that this guide to solar-terrestrial models will provide assistance to the large number of national and international projects and programs related to solar-terrestrial physics.

IONOSPHERE

The ionosphere is the region from about 50 km to 2000 km altitude, where the solar irradiance produces a partially ionized plasma. Neutral winds and electric fields determine the dynamics of the electron and ion gas. Above about 100 km, particle drifts are confined to the geomagnetic field lines.

Knowledge of the ionospheric **electron density** is essential for a wide range of applications, e.g., radio and telecommunications, satellite tracking, and Earth observation from space. Considerable efforts have, therefore, been concentrated on modeling this ionospheric parameter. Several models are described on the following pages including the phenomenological Chiu model, the Bent model that has been used extensively for satellite tracking, the semi-empirical SLIM model based on theoretically obtained grid values, and the recent FAIM model that uses the Chiu formalism together with the SLIM results. The International Reference Ionosphere (IRI) is probably the most mature of these models, having undergone more than two decades of scrutiny and improvement.

The ionospheric electron density profile exhibits several peaks with the *F2*-peak being the largest and most important. Several maps of spherical harmonic coefficients have been developed for the **F2-peak critical frequency *foF2*,** which is related to the peak density *NmF2* by

$$NmF2/m^{-3} = 1.24 \bullet 10^{10} \, (foF2/MHz)^2,$$

and for the **propagation factor *M(3000)F2***, which is related to the height of the *F2*-peak. This listing includes the widely used set of coefficients recommended by the International Radio Consultative Committee (CCIR), the set recently proposed by the International Union of Radio Science (URSI), and the mission-specific maps obtained by the Japanese Ionospheric Sounding Satellite-b (ISS-b) during 1978-1979. MINIMUF and IONCAP are software packages designed specifically for radio propagation purposes and are available from NOAA's World Data Center in Boulder, Colorado.

Fewer mostly mission-specific models have been developed for the **electron temperature, ion composition** (relative ion densities in percent) and the **ion drift**, the latter being closely related to the forcing electric field. The International Reference Ionosphere, the most complete representation of the ionosphere, includes models of the ion temperature, electron temperature, ion composition, and ion drift.

At present, almost all empirical models of ionospheric parameters are limited to non-auroral, magnetically quiet conditions. Major efforts are underway to extend ionospheric predictability beyond these limitations. A promising venue seems to be the inclusion of real-time data from the newly developed automatically recording and scaling ionosondes. These and other measurement techniques are discussed in a recent report published by NSSDC: D. Bilitza, *The Worldwide Ionospheric Data Base*, NSSDC 89-03, Greenbelt, Maryland, 1989. The ionospheric compendium includes also a chapter on the present status of ionospheric models.

At high latitudes, the plasma density and temperature are strongly affected by **electric fields** and by **particle precipitation**. Empirical modeling of the electric field and the electron and ion precipitation has shown great progress over the last decade as documented by the entries in this report. The auroral and polar zones are the regions of close coupling between ionosphere and magnetosphere. Both the electric (convection) field and the precipitating particles are of magnetospheric origin. The models are listed here rather than in the magnetospheric section because they were all established based on measurements at ionospheric altitudes by polar-orbiting satellites.

The Volland, Heelis, and Utah electric field models are semi-empirical in the sense that theoretically derived expressions are adapted to observed features. Empirical models have been developed from ground-based geomagnetic measurements (IZMIR model), from incoherent scatter data (Millstone Hill model), and from Dynamic Explorer (DE) satellite measurements (Heppner-Maynard-Rich model).

The AFGL models for the flux and energy of precipitating particles at auroral latitudes are based on DMSP satellite measurements at about 800 km altitude. The Rice model was established with Atmospheric Explorer-C (AE-C) and Atmospheric Explorer-D (AE-D) data. These models provide also the height-integrated ionospheric conductivities induced by precipitation of electrons. To obtain the total conductances, one has also to consider the UV/EUV-induced conductivities.

International Reference Ionosphere

1990

COSPAR/URSI Working Group on IRI
D. Bilitza
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
(301) 286-9536 SPAN: NCF::BILITZA

Parameter: Electron density, electron temperature, ion temperature, ion composition (O^+, H^+, He^+, NO^+, O_2^+)

Brief Description: The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a Working Group in the late sixties to produce an empirical standard model of the ionosphere, based on all available data sources. Several steadily improved editions of the model have been released. IRI describes the electron density, electron temperature, ion temperature, and ion composition in the altitude range from about 50 km to about 2000 km. It provides monthly averages in the non-auroral ionosphere for magnetically quiet conditions. Major data sources are the worldwide network of ionosondes, the powerful incoherent scatter radars (Jicamarca, Arecibo, Millstone Hill, Malvern, St. Santin), the ISIS and Alouette topside sounders, and in situ instruments on several satellites and rockets. IRI is updated yearly during special IRI workshops (e.g., during COSPAR general assembly). Several extensions are planned, including models for the ion drift, description of the auroral and polar ionosphere, and consideration of magnetic storm effects.

The IRI master copy is held at the National Space Science Data Center (NSSDC) and updated according to the decisions of the Working Group. The software package distributed by NSSDC includes a FORTRAN interactive driver program, subroutines, model coefficients, and documentation files. Required inputs are latitude, longitude, altitude, month, time (UT or LT), and solar activity (Rz_{12}).

Availability: On one tape, two diskettes (for use on PCs), SPAN, NSSDC's NODIS account (NSSDC ID #—Tape (unlabeled), **MI-91C**; tape (VAX), **MI-91D**; diskette, **MI-91E**; SPAN, **MI-91F**)

References:

K. Rawer, D. Bilitza, and S. Ramakrishnan, Goals and Status of the International Reference Ionosphere, *Rev. Geophys.*, 16, 177-181, 1978.

K. Rawer, S. Ramakrishnan, and D. Bilitza, International Reference Ionosphere 1978, International Union of Radio Science, *URSI Special Report*, 75 pp., Bruxelles, Belgium, 1978.

K. Rawer, J. V. Lincoln, and R. O. Conkright, International Reference Ionosphere—IRI 79, World Data Center A for Solar-Terrestrial Physics, *Report UAG-82*, 245 pp., Boulder, Colorado, 1981.

C. A. Barth, D. Offermann, K. Labitzke, J. I. Vette, K. Rawer, and H. A. Taylor (eds.), The Upper Atmosphere of the Earth and Planets, *Adv. Space Res.* 2, #10, 181-257, 1982.

K. Rawer and C. M. Minnis, Experience with and Proposed Improvements of the International Reference Ionosphere (IRI), World Data Center A for Solar-Terrestrial Physics, *Report UAG-90*, 235 pp., Boulder, Colorado, 1984.

K. Rawer, C. M. Minnis, and K. B. Serafimov (eds.), Towards an Improved International Reference Ionosphere, *Adv. Space Res.* 4, #1, 1984.

K. Rawer, C. M. Minnis, K. S. W. Champion (eds.), and M. Roemer, Models of the Atmosphere and Ionosphere, *Adv. Space Res.* 5, #7, 1-114, 1985.

K. Rawer and Y. V. Ramanamurty (eds.), International Reference Ionosphere– Status 1985/86, *Adv. Space Res.* 5, #10, 1985.

D. Bilitza, International Reference Ionosphere: Recent Developments, *Radio Sci.* 21, 343-346, 1986.

K. Rawer and P. A. Bradley (eds.), International Reference Ionosphere– Status 1986/87, *Adv. Space Res.* 7, #6, 1987.

K. Rawer, T. L. Gulyaeva, and B. W. Reinisch (eds.), Ionospheric Informatics, *Adv. Space Res.* 8, #4, 1988.

K. Rawer and D. Bilitza, Electron Density Profile Description in the International Reference Ionosphere, *J. Atmos. Terr. Phys.* 51, 781-790, 1989.

K. Rawer and P. A. Bradley (eds.), Ionospheric Informatics and Empirical Modeling, *Adv. Space Res.* 10, #8, 1990.

Chiu Ionospheric Model

1975

Y. T. Chiu
Lockheed Research Laboratory
3251 Hanover St.
Palo Alto, California 94304
SPAN: LOCKHD::CHIU

Parameter: Electron density

Brief Description: The global phenomenological model describes the large scale variations of ionospheric electron density with local time, latitude, and solar sunspot number. It is based on ionosonde data from 50 stations spanning the period 1957 to 1970. The model profile is obtained as the sum of three Modified Chapman functions for *E*-, *F1*-, and *F2*-layers. The model was improved by Chiu (1975) and served as the starting point for the FAIM model. The model is fairly simple, using less than 50 coefficients, which limits its application for equatorial and higher latitudes. It is, however, fast and easily manipulable and a good choice for first-order estimates. An extension for the polar cap ionosphere is being constructed.

Availability: On tape or SPAN (NSSDC ID #**MI-91A**)

References:

B. K. Ching and Y. T. Chiu, A Phenomenological Model of Global Ionospheric Electron Density in the *E*-, *F1*-, and *F2*-Regions, *J. Atmos. Terr. Phys.* 35, 1615, 1973.

Y. T. Chiu, An Improved Phenomenological Model of Ionospheric Density, *J. Atmos. Terr. Phys.* 37, 1563, 1975.

Bent Ionospheric Model

1972

R. B. Bent
DBA Systems Inc.
Melbourne, Florida 32901

Parameter: Electron density

Brief Description: The model describes the ionospheric electron density as a function of latitude, longitude, time, season, and solar radio flux. The topside is represented by a parabola and three exponential profile segments, and the bottomside by a bi-parabola. The model is based on about 50,000 Alouette topside ionograms (1962-1966), 6,000 Ariel 3 in situ measurements (1967-1968), and 400,000 bottomside ionograms (1962-1969). For the *F2*-peak the CCIR maps are used. The model has been widely used for ionospheric refraction corrections in satellite tracking. It does not include the lower layers (*D, E, F1*) and uses a simple quadratic relationship between CCIR's *M(3000)F2* factor and the height of the *F2*-peak. A comparison between the Bent model and the IRI model and their application for satellite orbit determination was discussed by Bilitza et al. (1988). IRI showed better results because of the more detailed representation of the bottomside density structure.

Availability: Model description on one microfiche (NSSDC ID #**MI-91G**)

References:

R. B. Bent, S. K. Llewellyn, and P. E. Schmid, A Highly Successful Empirical Model for the Worldwide Ionospheric Electron Density Profile, DBA Systems, Melbourne, Florida, 1972.

R. B. Bent, S. K. Llewellyn, and M. K. Walloch, Description and Evaluation of the Bent Ionospheric Model, DBA Systems, Melbourne, Florida, 1972. (B26740)

R. B. Bent, S. K. Llewellyn, and P. E. Schmid, Ionospheric Refraction Corrections in Satellite Tracking, *Space Research XII*, 1186-1194, Akademie-Verlag, Berlin, 1972.

P. Schmid, R. B. Bent, S. K. Llewellyn, G. Nesterczuk, and S. Rangaswamy, NASA-GSFC Ionospheric Correction to Satellite Tracking Data, Goddard Space Flight Center, *Report X-591-73-281*, Greenbelt, Maryland, 1973.

S. K. Llewellyn and R. B. Bent, Documentation and Description of the Bent Ionospheric Model, Air Force Geophysics Laboratory, *Report AFCRL-TR-73-0657*, Hanscom AFB, Massachusetts, 1973.

D. Bilitza, K. Rawer, and S. Pallaschke, Study of Ionospheric Models for Satellite Orbit Determination, *Radio Sci.* 23, 223, 1988.

Penn State Mk III Model 1985

J. S. Nisbet, R. Divany
Communications and Space Sciences Laboratory
316 Electrical Engineering East
The Pennsylvania State University
University Park, Pennsylvania 16802

Parameter: Ionospheric electron density and content

Brief Description: The Penn State Mk III model produces (1) tables of ionospheric electron densities from 120 km to 1250 km, (2) the ionospheric electron content, and (3) statistical properties of sporadic *E* occurrence. Two modes of operation are available. One generates two to 24 profiles throughout a day at one location, and the other generates a set of profiles at a range of locations at one universal time. The model combines theoretical computations with empirical models for the *F*-peak parameters. Mk III is an updated version of the earlier models developed at the Pennsylvania State University by Nisbet (1971) and Lee (1985). It uses the MSIS-83 atmospheric model, solar fluxes measured by the AE-E satellite (Hinteregger and Fukui, 1981), reaction rates from Torr et al. (1979), and the semi-empirical maps for the *F*-peak parameters developed by Rush et al. (1984). Meanwhile, most of these parameter models have been updated (e.g., see "URSI *foF2* Model Maps," page 2-9, and "MSIS Model," page 3-6), and these updates should be incorporated into the model code.

Availability: From the authors on one diskette for use on PCs equipped with math co-processor

References:

J. S. Nisbet, On the Construction and Use of a Simple Ionospheric Model, *Radio Sci.* 6, 437, 1977.

D. G. Torr et al., An Experimental and Theoretical Study of the Mean Diurnal Variation of O^+, NO^+, O_2^+, N_2^+ Ions in the Mid-Latitude *F1*-Layer of the Ionosphere, *J. Geophys. Res.* 84, 3360, 1979.

H. E. Hinteregger and K. Fukui, Observational Reference and Model Data on Solar EUV from Measurements on AE-E, *Geophys. Res. Lett.* 8, 1147, 1981.

C. M. Rush, M. PoKempner, D. N. Anderson, J. Perry, F. G. Stewart, and R. Reasoner, Maps of *foF2* Derived from Observations and Theoretical Data, *Radio Sci.* 19, 1083, 1984.

S. Lee, The Penn State Mark III Ionospheric Model: An IBM XT Computer Code, Pennsylvania State University, *Scientific Report PSU CSSL 482*, University Park, Pennsylvania, 1985.

SLIM Model

1985

D. N. Anderson
Air Force Geophysics Laboratory
Hanscom AFB, Massachusetts 01731
SPAN: AFGL::DANDERSON

M. Mendillo, B. Herniter
Department of Astronomy
Boston University
725 Commonwealth Avenue
Boston, Massachusetts 02215

Parameter: Electron density

Brief Description: The Semi-Empirical Low-Latitude Ionospheric Model (SLIM) is based on a theoretical simulation of the low latitude ionosphere. Electron density profiles (180 km to 1800 km) are determined for different latitudes (every 4° between 24° N and 24° S dip latitude) and local times (every hour) by solving the continuity equation for O^+ ions. The profiles are normalized to the *F2*-peak density and are then represented by Modified Chapman function using six coefficients per individual profiles. Calculations are performed for the equinox, June solstice, and December solstice, and for solar cycle minimum and maximum. In total the SLIM model consists of $3 \times 2 \times 13 \times 24 = 1{,}872$ profiles and $1{,}872 \times 6 = 11{,}232$ coefficients. Input parameters used in the theoretical calculation include the MSIS model neutral temperatures and densities, the IRI model temperature ratios and the diurnal ion drift patterns observed by the Jicamarca incoherent scatter radar for the different seasons (see also "FAIM Model" below).

Availability: The profile tables and coefficients are available from authors.

References:

D. N. Anderson, M. Mendillo, and B. Herniter, A Semi-Empirical, Low-Latitude Ionospheric Model, Air Force Geophysics Laboratory, *Report AFGL-TR-85-0254*, Hanscom AFB, Massachusetts, 1985.

D. N. Anderson, M. Mendillo, and B. Herniter, A Semi-Empirical Low-Latitude Ionospheric Model, *Radio Sci.* 22, 292, 1987.

FAIM Model

1989

D. N. Anderson, J. M. Forbes (See address above.)

Parameter: Electron density

Brief Description: The Fully Analytical Ionospheric Model (FAIM) uses the formalism of the Chiu model with coefficients fitted to the SLIM model profiles. The local time variation is expressed by a Fourier series up to order 6 and the variation with dip latitude by a fourth order harmonic oscillator function (Hermite polynomial).

Availability: FORTRAN code is available from authors on floppy disk or over SPAN.

References:

D. N. Anderson, J. M. Forbes, and M. Codrescu, A Fully Analytical, Low- and Middle-Latitude Ionospheric Model, *J. Geophys. Res.* 94, 1520, 1989.

J. M. Forbes, N. N. Anderson, M. Codrescu, and P. P. Batista, An Analytical/Empirical Model of the Middle and Low Latitude Ionosphere, Air Force Geophysics Laboratory, *Report GL-TR-89-0096*, Hanscom AFB, Massachusetts, 1989.

CCIR *foF2* and *M(3000)F2* Model Maps

1982

Comité Consultatif International des Radiocommunications
International Telecommunication Union
Place des Nations
CH-211 Geneva 20, Switzerland

Parameter: *F2*-peak parameters

Brief Description: This data set contains the coefficients for the *foF2* and *M(3000)F2* models recommended by the Comité Consultatif International des Radiocommunications (CCIR). *foF2* is the *F2*-peak plasma frequency, which is related to the *F2*-peak density *NmF2* by

$$NmF2/m^{-3} = 1.24 \cdot 10^{10} \, (foF2/\mathrm{MHz})^2.$$

M(3000)F2 (= MUF(3000)/*foF2*) is a propagation factor closely related to the height of the *F2*-peak (see Bilitza et al., 1979). MUF(3000) is the highest frequency that, refracted in the ionosphere, can be received at a distance of 3000 km. Both parameters *foF2* and *M(3000)F2* are routinely scaled from ionograms. The CCIR maps are based on monthly median values obtained by the worldwide network of ionosondes (about 150 stations) during the years 1954 to 1958, altogether about 10,000 station-months of data. Following a numerical mapping procedure developed by Jones and Gallet (1962, 1965), each station data set is first represented by a Fourier time series (in Universal Time), and then a worldwide development in a special form of Legendre functions (in geodetic latitude, longitude, and modified dip latitude) is applied for each Fourier coefficient. Coefficients sets are provided for high and low solar activity. For intermediate levels of solar activity, linear interpolation is suggested. The whole CCIR model consists of $(988 + 441) \cdot 2 \cdot 12 = 34{,}296$ coefficients.

Availability: On tape, diskette, SPAN (This data set is included in the International Reference Ionosphere.) (NSSDC ID #**MI-92C)**

References:

W. B. Jones and R. M. Gallet, The Representation of Diurnal and Geographic Variations of Ionospheric Data by Numerical Methods, *Telecomm. J.* 29, 129, 1962, and 32, 18, 1965.

CCIR Atlas of Ionospheric Characteristics, Comité Consultatif International des Radiocommunications, *Report 340-4*, International Telecommunications Union, Geneva, 1967.

W. B. Jones and D. L. Obitts, Global Representation of Annual and Solar Cycle Variation of *foF2* Monthly Median 1954-1958, U.S. Institute for Telecommunication Sciences, *Research Report OT/ITSRR 3*, National Technical Information Service, COM 75-11143/AS, Springfield, Virginia, 1970.

D. Bilitza, N. M. Sheikh, and R. Eyfrig, A Global Model for the Height of the *F2*-Peak Using *M(3000)F2* Values from the CCIR Numerical Map, *Telecomm. J.* 46, 549, 1979.

P. A. Bradely, Mapping the Critical Frequency of the *F2*-Layer: Part 1—Requirements and Developments to Around 1980, *Adv. Space Res.* 10, #8, 47, 1990.

URSI *foF2* Model Maps 1988

C. M. Rush
Institute for Telecommunication Sciences
National Telecommunications and Information Administration
325 Broadway
Boulder, Colorado 80303

Parameter: *F2*-peak plasma frequency, *foF2*

Brief Description: The URSI set of model coefficients is the result of efforts undertaken by the International Union of Radio Science (URSI) Working Group G.5. The numerical mapping method is the same as that explained for the CCIR *foF2* model. It has long been known that the CCIR model has its shortcomings above the oceans and in the southern hemisphere, where ionosonde measurements do not exist or are sparse. Rush et al. (1983, 1984) used aeronomic theory to fill the data gaps before applying the spherical harmonics mapping procedure. Fox and McNamara (1988) established the final URSI coefficients for the combined data base of Rush's values and about 45,000 station-months of ionosonde data (about 180 stations worldwide).

Availability: On tape, diskette, SPAN (This data set is included in the International Reference Ionosphere.) (NSSDC ID **#MI-92D**)

References:

C. M. Rush, M. PoKempner, D. N. Anderson, F. G. Stewart, and J. Perry, Improving Ionospheric Maps Using Theoretically Derived Values of *foF2*, *Radio Sci.* 18, 95, 1983.

C. M. Rush, M. PoKempner, D. N. Anderson, J. Perry, F. G. Stewart, and R. Reasoner, Maps of *foF2* Derived from Observations and Theoretical Data, *Radio Sci.* 19, 1083, 1984.

D. Bilitza, K. Rawer, S. Pallaschke, C. M. Rush, N. Matuura, and W. R. Hoegy, Progress in Modeling the Ionospheric Peak and Topside Electron Density, *Adv. Space Res.* 7, #6, 5, 1987.

K. Davies (Chairman), Report of URSI Working Group G.5 on Mapping of Characteristics at the Peak of the *F2*-Layer, *URSI Information Bulletin* 243, 93, 1987.

M. W. Fox and L. F. McNamara, Improved World-Wide Maps of Monthly Median foF2, *J. Atmos. Terr. Phys.* 50, 1077, 1988.

C. M. Rush, M. Fox, D. Bilitza, K. Davies, L. McNamara, F. Stewart, and M. PoKempner, Ionospheric Mapping: An Update of *foF2* Coefficients, *Telecomm. J.* 56, 179, 1989.

ISS-b *foF2* Maps 1981

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Parameter: *F2*-peak critical (plasma) frequency, *foF2*

Brief Description: This data set consists of six coefficients sets and a FORTRAN program to generate global *foF2* maps for different universal times (UT: 0, 1, 2, . . . 23). The model is based on measurements by the topside sounder aboard the Japanese ISS-b. Data were sampled into two-hour UT bins. Measurements from four consecutive months had to be combined to obtain a homogeneous global coverage. The exact sampling periods for the six sets of coefficients are 8/11-12/12/78, 10/10/78-2/11/79, 11/9/78-3/13/79, 1/10-5/14/79, 2/9-6/13/79, and 8/8-12/13/79. About 2,000 globally distributed data points are found for each of the periods in each of the UT bins. Spherical harmonics analysis is applied to these data points up to order 9 in modified dip latitude and to 4 in geographic longitude. The analysis method is explained in six reports of the Communications Research Laboratory for the six time periods. These reports also include global contour plots for different UTs and LTs. The ISS-b maps are for high solar activity, whereas the CCIR and URSI maps cover the whole solar activity range. Rush et al. (1989) showed that the new URSI model represents the ISS-b maps better than the older CCIR model.

Availability: On tape or SPAN (NSSDC ID **#78-018A-01A**)

References:

Atlas of Ionospheric Critical Frequency (foF2) Obtained from Ionospheric Sounding Satellite-b Observation, Part 1, August to December 1978 (1979); Part 2, October 1978 to March 1979 (1980); Part 3, January to June 1979 (1981); Part 4, August to December 1979 (1983), Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo, Japan.

N. Wakai and N. Matuura, Operation and Experimental Results of the Ionosphere Sounding Satellite-b, *Acta Astronautica* 7, 999, 1980.

N. Matuura, M. Kotaki, S. Miyazaki, E. Sagawa, and I. Iwamoto, ISS-b Experimental Results on Global Distributions of Ionospheric Parameters and Thunderstorm Activity, *Acta Astronautica* 8, 527, 1981.

C. M. Rush, M. Fox, D. Bilitza, K. Davies, L. McNamara, F. Stewart, and M. PoKempner, Ionospheric Mapping—An Update of *foF2* Coefficients, *Telecomm. J.* 56, 179, 1989.

MINIMUF/QSTMUF Model 1985

R. B. Rose
Naval Ocean Systems Center
San Diego, California 92152

Parameter: Maximal usable frequency for *HF* radio communication

Brief Description: This is a simplified prediction program for the maximal usable frequency (MUF) along an *HF* propagation path. The closer to MUF one operates, the more efficient the communications channel becomes. The model is based on a large number of oblique ionograms from a wide variety of sounding paths. Given the date, transmitter and receiver locations, and the solar flux index or sunspot number, hourly MUF values can be obtained.

Availability: The BASIC code on floppy disk for use on PCs is available ($30.00) from the National Geophysical Data Center, NOAA, Code E/GC2, 325 Broadway, Boulder, Colorado 80303.

References:

R. B. Rose, J. N. Martin, and P. H. Levine, MINIMUF-3: A Simplified *HF* MUF Prediction Algorithm, Naval Ocean Systems Center, *Report 186*, San Diego, California, 1978.

R. B. Rose, MINIMUF: A Simplified MUF Prediction Program for Microcomputers, *QST* 66(12), 36, 1982.

IONCAP Model 1983

L. R. Teters, J. L. Lloyd, G. W. Haydon, D. L. Lucas, F. G. Stewart
Institute for Telecommunication Sciences
National Telecommunications and Information Administration
325 Broadway, Boulder, Colorado 80303

Parameter: Electron density, maximum usable frequency, performance estimate for telecommunication systems

Brief Description: The Ionospheric Communications Analysis and Prediction Program (IONCAP) provides the means to calculate *HF* propagation parameters at any location. Field strength, mode reliability, the maximum usable frequency (MUF) and the lowest useful frequency (LUF) are some of the parameters calculated by IONCAP. They enable the user to specify antenna gains as a function of take-off angle and to specify required system performance in terms of the signal-to-noise ratio evaluated at the receiving point of the circuit. Required inputs include the transmitter and receiver location, transmitter power, universal time, month, and sunspot number.

Availability: An IBM PC version of IONCAP is available from the National Technical Information Service (**#PB84-111210**), Springfield, Virginia.

References:

L. R. Teters, J. L. Lloyd, G. W. Haydon, and D. L. Lucas, Estimating the Performance of Telecommunication Systems Using the Ionospheric Transmission Channel—Ionospheric Communications Analysis and Prediction Program User's Manual, National Telecommunication and Information Administration, *Report NTIA 83-127*, Boulder, 1983.

C. M. Rush, Ionospheric Radio Propagation Models and Predictions—A Mini-Review, *IEEE Trans. Antennas Propag.* AP-34, 1163, 1986.

Density Dependent Electron Temperature Model 1978

L. H. Brace and R. F. Theis
NASA/GSFC, Code 614
Greenbelt, Maryland 20771
SPAN: PACF::THEIS

Parameter: Electron temperature below 400 km

Brief Description: This model describes the daytime electron temperature in the altitude range 130 km to 400 km as a function of electron density N_e (in m^{-3}) and height h (in km).

$$T_e = 1051 + (17.01h - 2746) \bullet \exp(-5.122 \bullet 10^{-4}h + 6.094 \bullet 10^{12} N_e - 3.353 \bullet 10^{-14} h N_e)$$

It is based on AE-C Langmuir probe data from December 1973 to December 1974 between 50° north and south latitude and for solar zenith angles of less than 85°. An extended version including solar activity variations can be found in the International Reference Ionosphere (Bilitza et al., 1985).

References:

L. H. Brace and R. F. Theis, An Empirical Model of the Interrelationship of Electron Temperature and Density in the Daytime Thermosphere at Solar Minimum, *Geophys. Res. Lett.* 5, 275, 1978.

D. Bilitza, L. H. Brace, and R. F. Theis, Modeling of Ionospheric Temperature Profiles, *Adv. Space Res.* 5, #7, 53, 1985.

AEROS Electron Temperature Model 1979

K. Spenner
Institute für Physikalische Messtechnik
Heidenhofstr. 8
7800 Freiburg
Federal Republic of Germany

Parameter: Global electron temperature between 300 km and 700 km

Brief Description: This model provides the global electron temperature between 300 km and 700 km altitude for two local times (3 AM, 3 PM). It is based on data collected by the AEROS retarding potential analyzer through the first 100 days in 1973. Spherical harmonics up to degree and order 3 are used to describe the electron temperature as a function of geomagnetic latitude and longitude. Altitude variations are represented by a power series of degree 3. Two sets of the 36 coefficients each are listed, one for 3 PM and one for 3 AM.

Availability: ALGOL code may be available from the authors.

References:

K. Spenner and R. Plugge, Empirical Model of Global Electron Temperature Distribution Between 300 and 700 km Based on Data from AEROS-A, *J. Geophys.* 46, 43, 1979.

AE/ISIS Electron Temperature Models

1981

L. H. Brace and R. F. Theis
NASA/GSFC, Code 614
Greenbelt, Maryland 20771
SPAN: PACF::THEIS

Parameter: Electron temperature at 300 km, 400 km, 1400 km, and 3000 km

Brief Description: This data set includes several global empirical models of the ionospheric electron temperature. Two models (equinox and solstice) at 3000 km altitude based on ISIS 1 satellite data (1969-1970), three models (equinox, December solstice, June solstice) at 1400 km based on ISIS 2 data (1971-1972), two models (equinox, June solstice) each at 300 km and 400 km based on AE-C data (4/75-12/76, 2/77-6/78). A special form of spherical harmonics analysis is applied to the satellite data resulting in 81 coefficients per model. The coefficients describe the electron temperature variations as a function of dip latitude and local time up to order 8. These models are used in the International Reference Ionosphere (Bilitza et al., 1985).

Availability: On one tape, one diskette, SPAN as part of the International Reference Ionosphere (see page 2-3)

References:

L. H. Brace and R. F. Theis, Global Empirical Models of Ionospheric Electron Temperature in the Upper *F*-Region and Plasmasphere Based on in Situ Measurements from the Atmosphere Explorer-C, ISIS 1, and ISIS 2 Satellites, *J. Atmos. Terr. Phys.* 43, 1317, 1981.

D. Bilitza, L. H. Brace, and R. F. Theis, Modeling of Ionospheric Temperature Profiles, *Adv. Space Res.* 5, #7, 53, 1985.

DY Ion Composition Model

1985

A. D. Danilov, A. P. Yaichnikov
Institute of Applied Geophysics, U.S.S.R.
State Committee on Hydrometeorology
ul. Pavlik Morozov d. 12, Moscow
U.S.S.R.

Parameter: Ion composition (O^+, H^+, He^+, N^+, O_2^+, NO^+, Cluster ions), 75 km to 1000 km

Brief Description: This model describes the ionospheric ion composition as a function of altitude, solar zenith angle, latitude, solar radio flux, and month. It is based on an earlier model by Danilov and Semenov (1978) on satellite data from Electron 2, 4 and S3-1, and on data from 20 high apogee rocket flights. Fifty-four reference profiles were constructed for O^+, 18 for NO^+, O_2^+, H^+, He^+, and N^+, and six for Cluster ions. Simple analytical functions are used to represent the variation with altitude, solar zenith angle, latitude (only O^+, N^+, He^+, H^+), season (only NO^+, O_2^+, O^+, Cluster), and solar activity (all except Cluster).

Availability: On tape, diskette, SPAN as part of the International Reference Ionosphere (see page 2-3)

References:

A. D. Danilov and V. K. Semenov, Atmospheric Ion Composition Measurements Up to a Height of 170 km, *Space Research XIII*, 493, Akademie-Verlag, Berlin, 1973.

A. D. Danilov and V. K. Semenov, Relative Ion Composition Model at Mid-Latitudes, *J. Atmos. Terr. Phys.* 40, 1093, 1978.

A. D. Danilov and A. P. Yaichnikov, A New Model of the Ion Composition at 75 to 1000 km for IRI, *Adv. Space Res.* 5, 75, 1985.

ISR Ion Drift Model

1980

A. D. Richmond
High Altitude Observatory
National Center for Atmospheric Research
Boulder, Colorado 80307-3000
(303) 497-1546

Parameter: Ionospheric ion drift at 300 km (perpendicular to geomagnetic field)

Brief Description: The model describes the ion velocity at about 300 km altitude between -65° and +65° magnetic altitude. It is based on incoherent scatter radar (ISR) data from Millstone Hill (5/76-11/77), St. Santin (2/73-12/75), Arecibo (8/74-5/77), and Jicamarca (1/74-10/77). Only data for magnetically quiet periods are selected. They are averaged at each half hour for three seasons (November-February; May-August; March, April, September, October). For given magnetic latitude, longitude, universal time, and day number of the year the subroutine provides the drift velocity component perpendicular to the geomagnetic field and an electrostatic pseudo-potential, which can be used to obtain the ionospheric electric field.

Availability: On tape, SPAN (NSSDC ID **#MI-93B**)

References:

A. D. Richmond, M. Blanc, B. A. Emery, R. H. Wand, B. G. Fejer, R. F. Woodman, S. Ganguly, P. Amayenc, R. A. Behnke, C. Calderon, and J. V. Evans, An Empirical Model of Quiet-Day Ionospheric Electric Fields at Middle and Low Latitudes, *J. Geophys. Res.* 85, 4658, 1980.

St. Santin Ion Drift Model

1979

M. Blanc, P. Amayenc
L'Environment Terrestre et Planetaire
4 Avenue de Neptune
94107 Saint Maur Cedex
France

Parameter: Ion drift at 300 km (perpendicular to geomagnetic field)

Brief Description: The model describes the diurnal and seasonal variation of the *F*-region electric-field-induced plasma drift as measured by the St. Santin (44 N, 2 E) incoherent scatter radar. It was established on the basis of three years (1973-1975) of measurements during magnetically quiet periods. The ion velocity perpendicular to the geomagnetic field is represented by a simple harmonic function in local time with nine coefficients per season.

References:

M. Blanc and P. Amayenc, Seasonal Variations of the Ionospheric *ExB* Drifts Above Saint Santin on Quiet Days, *J. Geophys. Res.* 84, 2691, 1979.

Polar Cap Potential Drop Model 1981

P. H. Reiff, R. W. Spiro, T. W. Hill
Space Physics and Astronomy Department
Rice University, Box 1892
Houston, Texas 77251-1892

Parameter: Potential drop across polar cap

Brief Description: Simple linear relationships are given for the dependence of the potential drop across the polar cap on interplanetary parameters. The linear regression parameters are obtained by least-square fits to AE-C, AE-D, and S3-3 satellite data. Parameters are listed for the dependence on a variety of interplanetary parameters, including the solar wind velocity and the interplanetary magnetic field components. Variation with *Kp* is given by Senior et al. (1990).

References:

P. H. Reiff, R. W. Spiro, and T. W. Hill, Dependence of Polar Cap Potential Drop on Interplanetary Parameters, *J. Geophys. Res.* 86, 7639, 1981.

C. Senior, D. Fortaine, G. Claudal, D. Alcaydé, and J. Fontanari, Convection Electric Fields and Electrostatic Potential Observed with the EISCAT Facility, *Annales Geophysicae* 8, 257, 1990.

Volland Electric Field Model 1978

H. Volland
University of Bonn
Radioastronomical Institute
Auf dem Hügel 71, 5300 Bonn
Federal Republic of Germany

Parameter: Global electric potential and field

Brief Description: This is a simple analytical model based on a quasi-static electric potential field. An electric convection potential is introduced within the auroral zone. Semi-empirical analytical expressions are given for the horizontal components of the ionospheric electric field at all latitudes and local times. They are arranged to fit most general features of electric fields observed by polar-orbiting satellites. Magnetospheric electric fields are derived assuming a static magnetic dipole field and no parallel electric field. The model uses 18 coefficients. Two sets of coefficients are given, one for low and one for moderate geomagnetic activity.

References:

H. Volland, Models of the Global Electric Fields Within the Magnetosphere, *Am. Geophys.* 31, 159, 1975.

H. Volland, A Model of the Magnetospheric Electric Convection Field, *J. Geophys. Res.* 83, 2695, 1978.

H. Volland, Semi-Empirical Models of Magnetospheric Electric Fields, pp. 261-280, in: *Quantitative Modeling of Magnetospheric Processes*, W. P. Olson (ed.), American Geophysical Union, Washington, D.C., 1979.

Heelis Electric Convection Field Model

1982

R. A. Heelis, J. K. Lowell, R. W. Spiro
Center for Space Sciences, The University of Texas at Dallas
P.O. Box 688-083
Richardson, Texas 75080

Parameter: High-latitude electric potential and field, ion convection velocity

Brief Description: This mathematical model of the high latitude convection pattern is based on modifications to the Volland (1975) model (see "Volland Electric Field Model" above). It represents the general features of a two-cell convection pattern (IMF [Interplanetary Magnetic Field] southward) with a convection reversal boundary and a convection throat at noon. The model is simple and easily manipulable. A number of free parameters can be adjusted to customize the model for a particular application. The model can only be considered valid for southward IMF and does have some obvious limitations, such as no provision for overlapping of the two convection cells near noon. See "Utah Electric Convection Field Model" below and "Heppner-Maynard-Rich Electric Field Model," page 2-20, and references in each for comparisons with other models.

Availability: Available from authors (is included in Heppner-Maynard-Rich software package)

References:

R. A. Heelis, J. K. Lowell, and R. W. Spiro, A Model of the High-Latitude Ionospheric Convection Pattern, *J. Geophys. Res.* 87, 6339, 1982.

Utah Electric Convection Field Model

1986

J. J. Sojka, C. E. Rasmussen, R. W. Schunk
Center for Atmospheric and Space Sciences
UMC 3400, Utah State University
Logan, Utah 84322

Parameter: High-latitude electric potential and field, ion convection velocity

Brief Description: The model provides a description of the magnetospheric electric field at ionospheric altitudes. It uses a set of simple functions that are dependent on Kp and Interplanetary Magnetic Field (IMF) B_x, B_y, and B_z components. The functions and empirical relations are based on previous models (Heelis, Volland) and on satellite and incoherent scatter radar observations. The Kp index controls the cross-tail potential, the diameter of the polar cap, and the extent of the equatorial fall-off region. For southward IMF the model field depends only on IMF B_y. For northward IMF, a pair of extra convection cells exists inside the polar cap.

Availability: FORTRAN program may be available from the authors.

References:

J. J. Sojka, C. E. Rasmussen, and R. W. Schunk, An Interplanetary Magnetic Field Dependent Model of the Ionospheric Convection Electric Field, *J. Geophys. Res.* 91, 11281, 1986.

IZMIR Electric Field Model

1985

Y. I. Feldstein
Institute of Terrestrial Magnetism
Ionosphere and Radiowave Propagation (IZMIRAN)
142092, Troitsk
Moscow Region, U.S.S.R.

Parameter: Electric field, potential,and currents at high latitudes

Brief Description: This model consists of tables for several ionospheric high-latitude electric field and current parameters for three seasons (summer, winter, equinox). Each table row lists the hourly averages (MLT = 1 to 24) for a specific corrected geomagnetic latitude (CGL); there are 32 rows for CGL = 58 to 81 in steps of one degree. With the help of these tables, each parameter can be determined for the specific Interplanetary Magnetic Field (IMF) orientation (B_z, B_y). Different sets of tables are provided for $B_z > 0$ (quiet state) and $B_z < 0$ (disturbed state). For each state the parameters vary continuously with B_z and B_y. Eight parameters are given in this tabular format: (1) geomagnetic perturbation horizontal vector field at the Earth's surface, (2) electric field potential, (3) electric field vector, (4) field-aligned current, (5) transverse current vector, (6) equivalent current vector, and (7) current vector closing field-aligned current. These tables were computed at the Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation (IZMIRAN) in Moscow, based on the methods described by Faermark (1980). Electric field and currents are inferred from observed geomagnetic field variations with the help of the ionospheric conductivity model by Wallis and Budzinski (1981). Comparisons with KOSMOS 184 satellite data showed that a correcting multiplier of 3.5 was necessary for the computation of electric fields and currents. Richmond et al. (1988) use a similar but more self-consistent method to obtain potential, currents and fields in the high-latitude ionosphere from ground magnetometer and incoherent scatter measurements.

Availability: On one tape (This tape was provided by A. Feldstein from the World Data Center B2 in Moscow.) (NSSDC ID #**MI-93A**)

References:

D. S. Faermark, The Method of Calculation Electric and Magnetic Fields in High-Latitude Ionosphere, in: *Solar Wind and Magnetospheric Phenomena*, A. E. Levitin (ed.), p. 122, IZMIRAN, Moscow, 1980.

D. D. Wallis, E. E. Budzinski, Empirical Models of Height-Integrated Conductivities, *J. Geophys. Res.* 86, 125, 1981.

R. G. Afonina, B. A. Belov, V. Y. Gaidukov, L. A. Dremukhina, A. E. Levitin, D. S. Faermark, Y. I. Feldstein, Y. Z. Demidova, M. Y. Markova, The Model of Large-Scale Electric Field in the High Latitudes Based on the Geomagnetic Variations, in: *Geomagnetic Variations, Electric Fields, and Currents*, A. E. Levitin (ed.), p. 3, IZMIRAN, Moscow, 1983.

Y. I. Feldstein, A. E. Levitin, D. S. Faermark, R. G. Afonina, B. A. Belov, and V. Y. Gaidukov, Electric Fields and Potential Patterns in the High-Latitude Ionosphere for Different Situations in Interplanetary Space, *Planet. Space Sci.* 32, 907, 1984.

A. D. Richmond and Y. Kamide, Mapping Electrodynamic Features of the High-Latitude Ionosphere from Localized Observations: Technique, *J. Geophys. Res.* 93, 5741, 1988. (See also Richmond et al., same issue, 5760)

Millstone Hill Electric Field Model 1983

W. L. Oliver, J. M. Holt
MIT Haystack Observatory
Westford, Massachusetts 01886

Parameter: Auroral ion drift and electric field

Brief Description: This model consists of a sixth order polynomial in invariant magnetic latitude and an eighth order Fourier series in local time for the electric field components E_x (positive southward) and E_y (positive eastward). It represents the average electric field patterns observed by the Millstone Hill incoherent scatter radar in all of 1978. Three levels of geomagnetic activity (*Kp*) are considered. Averages were determined for half-hour intervals and for one degree intervals (from 60° to 75°). For recent updates, see Holt et al. (1986). Foster et al. (1986) used Millstone Hill data together with NOAA/TIROS precipitation data to develop convection (drift/electric field) models for different levels of a precipitation index.

Availability: From Millstone Hill

References:

J. V. Evans, J. M. Holt, and R. H. Wand, Millstone Hill Incoherent Scatter Observations of Auroral Convection Over 60° ≤ ^ ≤ 75°, 1. Observing and Data Reduction Procedures, *J. Geophys. Res.* 84, 7059, 1979.

J. V. Evans, J. M. Holt, W. L. Oliver, and R. H. Wand, Millstone Hill Incoherent Scatter Observations of Auroral Convection Over 60° ≤ ^ ≤ 75°, 2. Initial Results, *J. Geophys. Res.* 85, 41, 1980.

W. L. Oliver, J. M. Holt, R. H. Wand, and J. V. Evans, Millstone Hill Incoherent Scatter Observations of Auroral Convection Over 60° ≤ ^ ≤ 75°, 3. Average Patterns Versus *Kp*, *J. Geophys. Res.* 88, 5505, 1983.

J. M. Holt, R. H. Wand, J. V. Evans, and W. L. Oliver, Empirical Models for the Plasma Convection at High Latitudes from Millstone Hill Observations, *J. Geophys. Res.* 92, 203, 1987.

J. C. Foster, J. M. Holt, R. G. Musgrove, and D. S. Evans, Ionospheric Convection Associated with Discrete Levels of Particle Precipitation, *Geophys. Res. Lett.* 13, 656, 1986.

Heppner-Maynard-Rich Electric Field Model 1990

J. P. Heppner, N. C. Maynard, F. J. Rich
Space Physics Division
Air Force Geophysics Laboratory
Hanscom AFB
Bedford, Massachusetts 01731
SPAN: AFGL::RICH

Parameter: High-latitude electric potential and field, Pedersen and Hall conductances, field aligned currents, and Joule heating

Brief Description: This software package includes several electric convection field models, and the AFGL Precipitation and Conductivity Model; the latter for obtaining conductances, currents, and heating. The Heppner-Maynard models are based on OGO 6 (Polar-Orbiting Geophysical Observatory 6) and DE 2 (Dynamics Explorer 2) electric field measurements and provide the electric potential and field poleward of 60° geomagnetic latitude. Seven different models were generated for different Interplanetary Magnetic Field (IMF) conditions. Spherical harmonics to order 11 in magnetic local time and latitude are used in each case. For southward IMF, an explicit variability with geomagnetic activity is included. The Heelis Electric Convection Field Model is included in this package for comparative purposes. Rich and Maynard (1989) illustrate the improvements of their model in relation to the Heelis model and point out the differences to Foster et al. (1986) (see "Millstone Hill Electric Field Model" above) in the region of the Harang discontinuity and near the dayside cleft.

Availability: From the authors on tape, diskette, or SPAN

References:

J. P. Heppner, Empirical Models of High-Latitude Electric Fields, *J. Geophys. Res.* 82, 1115, 1977.

J. P. Heppner and N. C. Maynard, Empirical High-Latitude Electric Field Models, J. *Geophys. Res.* 92, 4467, 1987.

F. J. Rich and N. C. Maynard, Consequences of Using Simple Analytical Functions for the High-Latitude Convection Electric Field, *J. Geophys. Res.* 94, 3687, 1989.

Rice Electron Precipitation Model

1982

R. W. Spiro, P. H. Reiff, L. J. Maher
Department of Space Physics and Astronomy
Box 1892
Rice University
Houston, Texas 77251

Parameter: Precipitating electron energy flux, characteristic electron energy, Pedersen and Hall conductance in auroral zone

Brief Description: Data from the low energy electron experiment (LEE) on the AE-C and -D satellites have been used to determine the distribution of the energy flux of precipitating auroral electrons and their average energy for different levels of geomagnetic activity. The study is based on 30,407 individual measurements from January 1974 to April 1976. Tables of energy flux and characteristic energy were produced for four ranges of auroral electrojet indices (*AE*). Each table shows the variation with invariant latitude (30 bins between 50° and 88°) and magnetic local time (24 bins between 0 and 24). Empirical relationships are used to produce similar tables for the Pedersen and Hall conductances. Robinson et al. (1987) have pointed out errors in the calculation of conductances in the Rice model. Improvements were suggested by Kamide et al. (1989).

Availability: FORTRAN code may be available from the authors.

References:

R. W. Spiro, P. H. Reiff, and L. J. Maher, Precipitating Electron Energy Flux and Auroral Zone Conductances—An Empirical Model, *J. Geophys. Res.* 87, 8215, 1982.

R. M. Robinson, R. R. Vondrak, K. Miller, T. Dabbs, and D. Hardy, On Calculating Ionospheric Conductances from the Flux and Energy of Precipitating Electrons, *J. Geophys. Res.* 92, 2566, 1987.

Y. Kamide, Y. Ishihara, T. L. Killeen, J. D. Carven, L. A. Frank, and R. A. Heelis, Combining Electric Field and Aurora Observations from DE 1 and 2 with Ground Magnetometer Records to Estimate Ionospheric Electromagnetic Quantities, *J. Geophys. Res.* 94, 6723, 1989.

AFGL Electron Precipitation Model 1987

D. A. Hardy, M. S. Gussenhoven
Air Force Geophysics Laboratory
Hanscom AFB, Massachusetts 01731
SPAN: AFGL::HARDY

Parameter: Integral energy flux and number flux of precipitating auroral electrons, Pedersen and Hall conductivity

Brief Description: This model provides the integral energy and number flux of precipitating auroral electrons for seven levels of magnetic activity (Kp = 0, 1, 2, 3, 4, 5, and 6 and greater). It is based on about 14.1 million spectra (50 eV to 20 keV) from the SSJ/3 detectors on the DMSP F2 and F4 satellites and the CRL-251 detector on the P78-1 satellite. At each level of activity the high-latitude region was separated into 30 zones in corrected geomagnetic latitude (from 50° to 90°) and 48 one-half-hour zones in magnetic local time. Epstein transition functions are used to represent the spatial variation, and a Fourier series of order 6 is used to represent the temporal variation resulting in a total of 364 model coefficients. Coefficient sets were determined for the electron energy flux, the number flux, and the Pedersen and Hall conductivities. The latter is found with the help of empirical relationships between the conductivities and the electron energy flux and average energy.

Availability: FORTRAN code may be available from the authors (see "Heppner-Maynard-Rich Electric Field Model," page 2-20).

References:

D. A. Hardy, M. S. Gussenhoven, and E. Holeman, A Statistical Model of the Auroral Electron Precipitation, *J. Geophys. Res.* 90, 4229, 1985.

R. M. Robinson, R. R. Vondrack, K. Miller, T. Dabbs, and D. A. Hardy, On Calculating Ionospheric Conductivities from the Flux and Energy of Precipitating Electrons, *J. Geophys. Res.* 92, 2565, 1987.

D. A. Hardy, M. S. Gussenhoven, and R. Raistrick, Statistical and Functional Representations of the Pattern of Auroral Energy Flux, Number Flux, and Conductivity, *J. Geophys. Res.* 92, 12275, 1987.

AFGL Ion Precipitation Model 1989

D. A. Hardy, M. S. Gussenhoven, D. Brautigam
(See address above.)

Parameter: Integral energy flux, number flux, and average energy of precipitating auroral ions (30 eV to 30 keV)

Brief Description: This model provides the integral energy and number flux and the average energy of precipitating auroral ions as a function of corrected geomagnetic latitude (CGL), magnetic local time (MLT), and magnetic activity (Kp). About 26.5 million individual *1-s* spectra from the SSJ/4 detectors on the DMSP F6, and F7 satellites were sampled into 30 CGL bins (50° to 90°) and into 48 half-hour bins for seven levels of magnetic activity Kp = 0 to 6). The paper presents (1) plots of average spectra, (2) histograms of average integral energy/number flux and average energy as a function of CGL along the noon-midnight and dawn-dusk meridians, and (3) color-coded polar spectrograms of the same quantities in a MLT-CGL coordinate system.

References:

D. A. Hardy, M. S. Gussenhoven, and D. Brautigam, A Statistical Model of Auroral Ion Precipitation, *J. Geophys. Res.* 94, 370, 1989.

Auroral Oval Representation 1975

R. H. Holzworth, C.-I. Meng
Space Science Laboratory
University of California
Berkeley, California 94720

Parameter: Mathematical representation of the auroral oval

Brief Description: This model provides a mathematical representation of the auroral oval by a simple seven parameter Fourier series. Holzworth and Meng (1975) list coefficients for the seven Feldstein (1963) ovals which correspond to different levels of geomagnetic activity.

References:

Y. I. Feldstein, On Morphology and Auroral and Magnetic Disturbances at High Latitudes, *Geomagn. Aeron.* 3, 138, 1963.

R. H. Holzworth, C.-I. Meng, Mathematical Representation of the Auroral Oval, *Geophys. Res. Lett.* 2, 377, 1975.

Auroral Absorption Model 1983

A. J. Foppiano, P. A. Bradley
Rutherford Appleton Laboratory
Chilton, Didcot, Oxon OX11 0QX
United Kingdom

Parameter: Probability that absorption at 30 MHz exceeds *1dB*; median absorption

Brief Description: This model provides information for *HF* propagation calculations at high latitudes. It is based on the long record of worldwide riometer measurements. The model describes the probability Q_1 that the *HF* absorption exceeds *1dB*. Q_1 is a parameter important for long term predictions. Simple empirical expressions are given for the dependence on corrected geomagnetic latitude, longitude, and local time, solar activity (12 months smoothed sunspot number), and season. Assuming a log-normal distribution for the cumulative absorption probability, the authors deduce a simple linear relationship between Q_1 and the median absorption.

Availability: PC software may be available from the authors.

References:

A. J. Foppiano and P. A. Bradley, Prediction of Auroral Absorption of High-Frequency Waves at Oblique Incidence, *Telecomm. J.* 50, 547, 1983.

A. J. Foppiano and P. A. Bradley, Day-to-Day Variability of Riometer Absorption, *J. Atmos. Terr. Phys.* 46, 689, 1984.

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ATMOSPHERE

The atmosphere can roughly be characterized as the region from sea level to about 1000 km altitude around the globe, where neutral gases can be detected. Below 50 km the atmosphere can be assumed to be homogeneously mixed and can be treated as a perfect gas. Above 80 km the hydrostatic equilibrium gradually breaks down as diffusion and vertical transport become important. The major species in the upper atmosphere are N_2, O, O_2, H, He. Temperature-oriented nomenclature differentiates the strata of the atmosphere as follows: the troposphere, from sea level up to about 10 km, where the temperature decreases; the stratosphere, from 10 km up to about 45 km, where the temperature increases; the mesosphere, from 45 km up to about 95 km, where the temperature decreases again; the thermosphere, from 95 km to about 400 km, where the temperature increases again; and the exosphere, above about 400 km, where the temperature is constant. The first global models of the upper atmosphere were developed by L. G. Jacchia in the early sixties based on theoretical considerations and satellite drag data. Since the launch of Sputnik 1 in 1957, orbit decay of artificial satellites has been used to derive atmospheric data.

Several national and international organizations have established committees for the development of atmospheric reference models, e.g., the International Civil Aviation Organization (ICAO), the Committee on Space Research (COSPAR), and the Committee on Extension to the Standard Atmosphere (COESA). Probably the most widely used and well established model is the COSPAR International Reference Atmosphere (CIRA), an effort that started in 1961 with the publication of CIRA-61. CIRA-72, the third generation of this model, includes Jacchia's 1971 model.

With the launch of the OGO 6 satellite in 1969, in situ measurements of atmospheric parameters by mass spectrometer became available. At about the same time, ground-based incoherent scatter radars started to monitor the thermospheric temperature. A. E. Hedin and his co-workers combined data from these two data sources to establish the Mass Spectrometer Incoherent Scatter (MSIS) models: MSIS-77, -83, -86. The CIRA and MSIS groups joined forces in 1986; MSIS-86 constitutes the upper part of CIRA-86.

Description of storm effects remains one of the most challenging topics in thermospheric modeling. DE-2 wind measurements have shown characteristic high-latitude wind signatures caused by similar IMF (Interplanetary Magnetic Field)-dependent signatures in ionospheric convection.

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U.S. Standard Atmosphere 1976

National Geophysical Data Center
National Oceanic and Atmospheric Administration
325 Broadway
Boulder, Colorado 80303
(303) 497-6136

Parameter: Atmospheric density, temperature, and pressure

Brief Description: The work of the U.S. Committee on Extension to the Standard Atmosphere (COESA), established in 1953, led to the 1958, 1962, 1966, and 1976 versions of the U.S. Standard Atmosphere. These models were published in book form jointly by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the U.S. Air Force. Altogether 30 U.S. organizations representing government, industry, research institutions, and universities participated in the COESA effort. Based on rocket and satellite data and perfect gas theory, the atmospheric densities and temperatures are represented from sea level to 1000 km. Below 32 km the U.S. Standard Atmosphere is identical with the Standard Atmosphere of the International Civil Aviation Organization (ICAO). The U.S. Standard Atmospheres 1958, 1962, and 1976 consist of single profiles representing the idealized, steady-state atmosphere for moderate solar activity. Parameters listed include temperature, pressure, density, acceleration caused by gravity, pressure scale height, number density, mean particle speed, mean collision frequency, mean free path, mean molecular weight, sound speed, dynamic viscosity, kinematic viscosity, thermal conductivity, and geopotential altitude. The altitude resolution varies from 0.05 km at low altitudes to 5 km at high altitudes. All tables are given in English (foot) as well as metric (meter) units. The U.S. Standard Atmosphere Supplements, 1966 includes tables of temperature, pressure, density, sound speed, viscosity, and thermal conductivity for five northern latitudes (15, 30, 45, 60, 75), for summer and winter conditions.

Availability: In hard copy from the National Geophysical Data Center (NGDC)

References:

U.S. Extension to the ICAO Standard Atmosphere, U.S. Government Printing Office, Washington, D.C., 1958.

U.S. Standard Atmosphere, 1962, U.S. Government Printing Office, Washington, D.C., 1962.

U.S. Standard Atmosphere Supplements, 1966, U.S. Government Printing Office, Washington, D.C., 1966.

U.S. Standard Atmosphere, 1976, U.S. Government Printing Office, Washington, D.C., 1976.

Jacchia Reference Atmosphere 1977

L. G. Jacchia
Smithsonian Astrophysical Observatory
Cambridge, Massachusetts

Parameter: Density and temperature in upper atmosphere

Brief Description: The Jacchia Reference Atmospheres were published as reports in 1970, 1971, and 1977. These publications include explanatory text, formulas, and tables. The density, temperature, and composition are listed in the altitude range 90 km to 2500 km. Variations with season, latitude, and local time are considered. Auxiliary tables are provided to evaluate geomagnetic, semi-annual, and seasonal-latitudinal effects. Jacchia's models are based mostly on satellite drag data. Assuming diffusive equilibrium, the atmospheric profiles are defined by the exospheric temperature. He contributed the thermospheric part (110 km to 200 km) to the CIRA-72 model. Jacchia (1964) was the first to point out the coupling between solar wind and atmosphere.

Availability: On microfiche (Jacchia 1970 Reference Atmosphere, NSSDC ID #**MN-30A**; Jacchia 1971, #**MN-31A**; Jacchia 1977, #**MN-37A**).

References:

L. G. Jacchia, Static Diffusion Models of the Upper Atmosphere with Empirical Temperature Profiles, *Smithson. Astrophys. Obs. Spec. Rept. No. 170*, Cambridge, Massachusetts, 1964.(B08448)

L. G. Jacchia, Revised Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles, *Smithson. Astrophys. Obs. Spec. Rept. No. 332*, 1971. (B10091)

L. G. Jacchia, Thermospheric Temperature, Density, and Composition: New Models, *Smithson. Astrophys. Obs. Spec. Rept. No. 375*, 1977. (B29307)

Atmospheric Handbook 1984

National Geophysical Data Center
NOAA/NESDIS E/GC2
325 Broadway
Boulder, Colorado 80303
(303) 497-6136

Parameter: Atmospheric parameters for scattering, radiation, and emission calculations

Brief Description: This data set was compiled by V. E. Derr and is available in hard copy and on magnetic tape. The parameters were collected over many years in response to requests by researchers for atmospheric electromagnetic wave propagation. Data presented include attenuation coefficients for the atmosphere and H_2O; 1962 Standard Atmospheres; cloud drop size distributions for water and ice spheres; solar spectral irradiance; sky spectral radiance; Rayleigh coefficients for air; refractive indices for air, ice, liquid H_2O, and various atmospheric aerosols; and relative reflectance for ice and H_2O.

Availability: In hard copy and on one magnetic tape from NGDC

References:

V. E. Derr, Atmospheric Handbook: Atmospheric Data Tables Available on Computer Tape, World Data Center A for Solar-Terrestrial Physics, *Report UAG-89*, Boulder, Colorado, 1984.

COSPAR International Reference Atmosphere: 0 km to 120 km

1986

CIRA Working Group
Sushil Chandra, NASA/GSFC, Code 916
Greenbelt, Maryland 20771

Parameter: Neutral temperature, zonal wind, pressure, geopotential height (0 km to 120 km)

Brief Description: The COSPAR International Reference Atmosphere (CIRA) provides empirical models of atmospheric temperature and densities from 0 km to 2000 km as recommended by the Committee on Space Research (COSPAR). Since the early sixties different editions of CIRA have been published: CIRA 1961, CIRA 1965, CIRA 1972. The CIRA Working Group meets bi-annually during the COSPAR general assemblies. In the thermosphere (above about 100 km) CIRA-86 is identical to the MSIS-86 model (see "MSIS Model," page 3-6).

The software package presented here includes only the lower part (0 km to 120 km) of CIRA-86. It consists of tables of the monthly mean values of temperature and zonal wind for the latitude range 80°N to 80°S. Two files exist, one in pressure coordinates, including also the geopotential heights, and one in height coordinates, including also the pressure values. These tables were generated by Fleming et al. (1988) from several global data compilations including ground-based and satellite (Nimbus 5, 6, 7) measurements: Oort (1983), Labitzke et al. (1985). The lower part was merged with MSIS-86 at 120 km altitude. In general, hydrostatic and thermal wind balance is maintained at all levels. The model accurately reproduces most of the characteristic features of the atmosphere, such as the equatorial wind and the general structure of the tropopause, stratopause, and mesopause.

Availability: On one tape, one diskette (for use on PCs), SPAN (NSSDC ID #**MN-17A**)

References:

CIRA 1961, H. Kallmann-Bijl, R. L. F. Boyd, H. Lagow, S. M. Poloskov, and W. Priester (eds.) North-Holland Publishing Company, Amsterdam, 1961.

CIRA 1965, North-Holland Publishing Company, Amsterdam, 1965.

CIRA 1972, Akademie-Verlag, Berlin, German Democratic Republic, 1972.

A. H. Oort, Global Atmospheric Circulation Statistics 1958-1983, National Oceanic and Atmospheric Administration, *Professional Paper 14*, 180 pp., U.S. Government Printing Office, Washington, D.C., 1983.

K. Labitzke, J. J. Barnett, and B. Edwards (eds.), Middle Atmosphere Program, *MAP Handbook*, Volume 16, University of Illinois, Urbana, 1985.

K. Rawer, C. M. Minnis, K. S. W. Champion, and M. Roemer (eds.), Models of the Atmosphere and Ionosphere, *Adv. Space Res.* 5, #7, 1985.

K. U. Grossmann, K. S. W. Champion, and M. Roemer, W. L. Oliver, and T. A. Blix (eds.), The Earth's Middle and Upper Atmosphere, *Adv. Space Res.* 7, #10, 1987.

E. L. Fleming, S. Chandra, M. R. Shoeberl, and J. J. Barnett, Monthly Mean Global Climatology of Temperature, Wind, Geopotential Height and Pressure for 0-120 km, National Aeronautics and Space Administration, *Technical Memorandum 100697*, Washington, D.C., 1988.

M. J. Rycroft, G. M. Keating, D. Rees (eds.), Upper Atmosphere Models and Research, *Adv. Space Res. 10*, #6, 1990 (includes the article by Fleming et al., 1988).

COSPAR International Reference Atmosphere: Thermosphere 1986

CIRA Working Group
D. Rees
Department of Physics and Astronomy
University College, London
United Kingdom

Parameter: Neutral temperature and densities in the thermosphere

Brief Description: The COSPAR International Reference Atmosphere (CIRA) provides empirical models of atmospheric temperature and densities (see above for more information). Above 120 km, in the thermosphere, CIRA-86 is identical with the MSIS-86 model (see "MSIS Model" below). In addition to the empirical model, CIRA-86 includes the theoretical thermosphere model of D. Rees and his colleagues at University College, London. Results from 50 global simulations with this model have been stored in computer-readable form and can be reconstructed on VAX or PC computers.

Availability: MSIS-86 (see "MSIS Model" below). Data base of theoretical profiles on diskette is available from D. Rees.

References:

CIRA 1986, Part I: Thermosphere Model, D. Rees (ed.), *Adv. Space Res.* 8, #5-#6, 1988.

S. Batten, T. J. Fuller-Rowell, and D. Rees, A Numerical Data Base for VAX and Personal Computers for Storage, Reconstruction, and Display of Global Thermospheric and Ionospheric Models, *Planet. Space Sci.* 35, 1167, 1987.

MSIS Model

1986

A. E. Hedin
NASA/GSFC, Code 914
Greenbelt, Maryland 20771
SPAN: PACF::HEDIN

Parameter: Neutral densities and temperature of the thermosphere

Brief Description: The Mass-Spectrometer-Incoherent-Scatter (MSIS) model describes the neutral temperature and densities in the upper atmosphere (above about 100 km). MSIS-86 constitutes the upper part of the COSPAR International Reference Atmosphere (CIRA) 1986. The MSIS model is based on the extensive data compilation and analysis work of A. E. Hedin and his colleagues. Data sources include measurements from several rockets, satellites (OGO 6, San Marco 3, AEROS-A, AE-C, AE-D, AE-E, ESRO 4, and DE 2), and incoherent scatter radars (Millstone Hill, St. Santin, Arecibo, Jicamarca, and Malvern). The model expects as input year, day of year, Universal Time, altitude, geodetic latitude and longitude, local apparent solar time, solar *F10.7* flux (for previous day and three-month average), and magnetic *Ap* index (daily or *Ap* history for the last 59 hours). For these conditions the following output parameters are calculated: number density of He, O, N_2, O_2, Ar, H, and N, total mass density; neutral temperature and exospheric temperature. For diagnostic purposes the source code is equipped with 23 flags to turn on/off particular variations. Hedin (1988) compared all three MSIS models with each other and with the Jacchia 1970 and 1977 models.

Availability: On one tape, one diskette (for use on PCs), SPAN, NSSDC's NODIS account (NSSDC ID # – Tape (foreign), **MN-61B**; tape (VAX), **MN-61A**; diskette, **MN-61D**; SPAN, **MN-61C**)

References:

A. E. Hedin, J. E. Salah, J. V. Evans, C. A. Reber, G. P. Newton, N. W. Spencer, D. C. Kayser, D. Alcayde, P. Bauer, L. Cogger, and J. P. McClure, A Global Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data, *J. Geophys. Res.* 82, 2139-2156, 1977.

A. E. Hedin, A Revised Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data: MSIS-83, *J. Geophys. Res.* 88, 10170-10188, 1983.

A. E. Hedin, MSIS-86 Thermospheric Model, *J. Geophys. Res.* 92, 4649, 1987.

A. E. Hedin, High Altitude Atmospheric Modeling, *NASA Technical Memorandum 100707*, Scientific and Technical Information Office, Washington, D.C., 1988.

A. E. Hedin and G. Thuillier, Comparison of OGO 6 Measured Thermospheric Temperatures with the MSIS-86 Empirical Model, *J. Geophys. Res.* 93, 5965-5971, 1988.

Horizontal Wind Model (HWM) 1987

A. E. Hedin
NASA/GSFC, Code 914
Greenbelt, Maryland 20771
SPAN: PACF::HEDIN

Parameter: Horizontal neutral wind in the upper atmosphere

Brief Description: The HWM87 is an empirical model of the horizontal neutral wind in the upper thermosphere. It is based on wind data obtained from the AE-E and DE 2 satellites. A limited set of vector spherical harmonics is used to describe the zonal and meridional wind components. The data base was not adequate to detect solar cycle effects, but the model does include magnetic activity effects. Mid- and low-latitude data are reproduced quite well by the model. The polar vortices are present, but not to full detail. Currently, the model is intended for winds above 220 km altitude; it does not include altitude variations. The model software provides zonal and meridional winds for specified latitude, longitude, time, and *Ap* index. A comparison of the HWM values with winds derived from IRI parameters and from ionosonde measurements have shown in general good agreement (Miller et al., 1990).

Availability: On one tape, one diskette (for use on PCs), SPAN (NSSDC ID **#MN-61E**)

References:

A. E. Hedin, N. W. Spencer, and T. L. Killeen, Empirical Global Model of Upper Thermosphere Winds Based on Atmosphere and Dynamics Explorer Satellite Data, *J. Geophys. Res.* 93, 9959-9978, 1988.

K. L. Miller, A. E. Hedin, P. J. Wilkinson, D. G. Torr, and P. G. Richards, Neutral Winds Derived from IRI Parameters and from the HWM87 Wind Model for the SUNDIAL Campaign of September, 1986, *Adv. Space Res.* 10, #8, 99, 1990.

MAGNETOSPHERE

The magnetosphere is the volume of space dominated by the Earth's magnetic field. Solar wind compresses the dayside magnetosphere and stretches the nightside into a comet-like tail millions of miles long. The Earth's radiation belts in the inner magnetosphere were one of the first major discoveries of the satellite age. They consist of trapped electrons and protons that gyrate rapidly around geomagnetic field lines, travel back and forth less rapidly along geomagnetic field lines between conjugate points in opposite hemispheres, and drift slowly around the Earth.

Quite a number of empirical models have been developed for the Earth's magnetic field. The internal source field models represent the **Earth's main (core) magnetic field** for magnetically quiet conditions ($Kp \leq 1$). As shown by Gauss in 1839, the potential of the geomagnetic field can be represented by a spherical harmonic series, the first term being the simple dipole term. The gradient of the potential determines the magnetic vector field. The Earth's real magnetic field is the sum of several contributions including the main (core) field, the crustal (anomaly) field, and external source fields. The core contribution dominates the field from the Earth's surface up to about four Earth radii. The principal data sources for main field modeling are (1) permanent magnetic observatories, (2) repeat measurements at selected sites, (3) surveys from aircraft and ships, and (4) global satellite measurements. Whereas the Cosmos 49 (October and November 1964) and OGO 2, 4, 6 (October 1965 through July 1971) satellites provided only the field magnitude, the MAGSAT and DE spacecraft were capable of measuring the field magnitude and direction. Satellite data have also helped to evaluate the crustal (anomaly) fields at individual observatories and have thus greatly enhanced the accuracy of observatory data for main field modeling. Temporal variations of the internal field have been modeled by expanding the coefficients in a Taylor series in time. Most models include only the constant and first time derivative (secular variation) terms. Some recent models have incorporated the second and third derivative terms, too (see the Summary Table, page 4-3).

The main field models listed on the following pages differ in the data base used, in the number of coefficients (i.e., degree/order of Legendre polynomials and Taylor series expansion), and in the epoch represented. All coefficient sets are based on the usual Schmidt quasi-normalized form of associated Legendre functions. It is recommended in all cases to use a specific model only for the time period covered by the data base on which the specific model is based.

The main field software package consists in most cases of the coefficients only. Programs to calculate geomagnetic parameters from these sets of coefficients are also available from the National Space Science Data Center (NSSDC) (see below).

Beyond four Earth radii, the Earth's magnetic field is increasingly affected by the impinging solar wind. The distortions can be described by several **external source fields** caused by current systems. One can identify three main current systems in the undisturbed outer magnetosphere: (1) a current system on the magnetospheric boundary (magnetopause), (2) a current system in the neutral sheet of the geomagnetic tail (the surface that separates the two lobes of the tail), and (3) a current system around the Earth (ring current) flowing in the equatorial (minimum B) surface. During geomagnetic storms and substorms substantial changes occur in these systems, in addition to the appearance of field-aligned currents flowing out of and into the lower ionosphere. The software packages listed in this category include the coefficients and programs to calculate the external as well as internal contributions to the geomagnetic field.

This section also lists several **computer programs related to geomagnetic models** including software (1) to compute the geomagnetic field strength B and its vector components and the L-shell value, (2) to convert between different coordinate systems (see also Appendix B), and (3) for magnetic field-line tracing. L is McIlwain's (1961) shell parameter, which at the magnetic equator corresponds to the radial distance from the Earth's center expressed in units of Earth radii. In the case of a dipole magnetic field (no multipole terms), the parameter L labels the dipole field lines. In the case of the real field, however, L varies along a field line, although the variation is less than 1% in the inner magnetosphere. L is defined as a function of the adiabatic invariant I; I is the curve integral over the particle momentum (parallel to the magnetic field) integrating along the field line between conjugate points. The functional dependence between L and I was determined for a pure dipole field and was then also used for the real field.

The widely used and recommended International Geomagnetic Reference Field (main field only) and Tsyganenko Magnetic Field Model (with external sources) packages include software for B, L calculation and field-line tracing, and an interactive driver, which simplifies access to these models.

The **flux of trapped electrons and protons** in the **Earth's radiation belt** has been measured by a large number of satellites over the last three decades. Knowledge of the particle environment is essential for estimates of the radiation exposure of humans and materials in space. J. Vette and his colleagues at NSSDC have developed and improved empirical models for the trapped particle fluxes since the mid-sixties. The particle fluxes can best be described in terms of the coordinates B/B_O and L; B_O is the magnetic field strength at the magnetic equator (minimum value). Application of these models requires, therefore, the use of a geomagnetic field model.

Summary Table: Internal Source Models

Model Name	Number of Coeff.	Degree/Order Main	1.	2.	3.	Data Base	Epoch	Page
Jensen, Cain	48	6				1945 - 1962	1960	4-4
GSFC 9/65	147	9	6			1945 - 1964	1960	4-4
GSFC 12/66	360	10	10	10		1900 - 1966	1960	4-5
GSFC 9/80	462	13	13	6	4	OGO, MAGSAT, 1960-1980	1980	4-10
GSFC 12/83	367	14	11			MAGSAT, 1978-1982	1980	4-10
GSFC 11/87	448	14	14			DE, MAGSAT, 1978-1983	1982	4-12
POGO 3/68	198	9	9			OGO	1960	4-5
POGO 10/68	286	11	11			OGO	1960	4-6
POGO 8/69	240	10	10			OGO 1965.7 to 1968.4	1960	4-6
POGO 8/71	240	10	10			OGO Dec. 1965 to Mar. 1970	1960	4-7
MGST 6/80	195	13				MAGSAT Nov. 5-6, 1979	1979.85	4-9
MGST 4/81	258	13	7			MAGSAT 15 days	1980	4-9
Barraclough-75	296	12	8	6		Aircr., OGO, Obs.	1975	4-8
USGS, ACW75	248	12	8			1967-1974	1975	4-8
USGS, Cont. U.S.	24	4				Land, Marine, Aerial	1985	4-11
USGS, Hawaii	8	2				Surveys, IGRF	1985	4-11
IGRF, 1987	120	10				All Data Sources	1945-85	4-11

Jensen-Cain Model Coefficients 1962

J. C. Cain
Department of Geology
Florida State University
Tallahassee, Florida 32306-3026

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the coefficients associated with the Gauss-normalized Legendre polynomials in the potential expansion for the Jensen-Cain geomagnetic field model. The coefficients are for epoch 1960.0 and are based on about 74,000 ground observations of *H* and *F* since 1940. There are 48 non-zero coefficients extending up to order and degree 6. Secular variations of the field are not considered, i.e., no time derivative coefficients. The oblateness of the Earth has not been taken into account in the determination of the coefficients. Compared with more recent models, the accuracy of this model is poor. It was, however, widely used in the calculation of geomagnetic coordinates for the early satellite missions. Geomagnetic field parameters can be generated with the FIELDG (**#PG-11A**) program.

Availability: On one tape, SPAN (NSSDC ID **#MG-11A**)

References:

D. C. Jensen and J. C. Cain, An Interim Geomagnetic Field, *J. Geophys. Res.* 67, 3568, 1962.

GSFC (9/65) Model Coefficients 1966

J. C. Cain
(See address above.)

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 147 coefficients of the GSFC (9/65) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1960.0 and are based on about 197,000 survey data gathered between 1945 and 1964. The coefficients extend up to degree and order 9 in the constant term and to degree and order 6 in the first time derivative. The oblateness of the Earth (flattening factor of 1/298.3) has been considered in the determination of the coefficients. Geomagnetic field parameters can be generated with the ALLMAG (**#PG-12A**) program.

Availability: On one tape, SPAN (NSSDC ID **#MG-12A**)

References:

S. J. Hendricks and J. C. Cain, Magnetic Field Data for Trapped-Particle Evaluation, *J. Geophys. Res.* 71, 346, 1966.

GSFC (12/66) Model Coefficients 1967

J. C. Cain
Department of Geology
Florida State University
Tallahassee, Florida 32306-3026

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 360 coefficients of the GSFC (12/66) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1960.0 and extend up to degree and order 10 in the constant, first derivative and second derivative terms. In addition to all available survey data from 1900 to 1964, the model is based on some Vanguard 3 and Alouette satellite data and on preliminary field observation by OGO 2 from October 29 to November 15, 1965. Use of this model beyond 1965 is not recommended. Geomagnetic field parameters can be generated with the ALLMAG programs (#**PG-12A**).

Availability: On one tape, SPAN (NSSDC ID #**MG-13A**)

References:

J. C. Cain, S. J. Hendricks, R. A. Langel, and W. V. Hudson, A Proposed Model for the International Geomagnetic Reference Field, 1965, *J. Geomag. Geoelectr.* 19, 335, 1967.

POGO (3/68) Model Coefficients 1968

J. C. Cain
(See address above.)

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 198 coefficients of the POGO (3/68) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1960.0 and extend up to degree and order 9 in the constant and first derivative terms. The model is based on field strength data obtained with the (Polar) Orbiting Geophysical Observatory (POGO or OGO) satellites from October 12, 1965, to August 2, 1967 (mostly OGO 2, some early OGO 4 data). Altogether 22,252 data points were used in establishing POGO (3/68). The model represents the OGO data much better than the older GSFC (12/66) model and was submitted as candidate for the International Geomagnetic Reference Field (see Cain and Langel, 1971).

Availability: On one tape, SPAN (NSSDC ID #**MG-16A**)

References:

J. C. Cain and S. J. Cain, Derivation of the International Geomagnetic Reference Field, IGRF (10/68), Goddard Space Flight Center, *Report X-612-68-501*, Greenbelt, Maryland, 1968.

J. C. Cain and R. A. Langel, Geomagnetic Survey by the Polar-Orbiting Geophysical Observatories, in: World Magnetic Survey 1957-1969, A. J. Zimuda (ed.), 65-75, *IAGA Bulletin*, No. 28, International Union of Geodesy and Geophysics, Paris, 1971.

POGO (10/68) Model Coefficients 1968

J. C. Cain
Department of Geology
Florida State University
Tallahassee, Florida 32306-3026

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 286 coefficients of the POGO (10/68) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1960.0 and extend up to degree and order 11 in the constant and first derivative terms. In addition to all the data used in POGO (3/68), the model is based on OGO 4 field strength data until December 1967. Altogether 32,649 data points were considered in establishing POGO (6/68). Improvements over POGO (3/68) resulted not only from the extended data base but also from using more accurate orbital positions for OGO 2.

Availability: On one tape, SPAN (NSSDC ID **#MG-17A**)

References:

J. C. Cain and R. A. Langel, The Geomagnetic Survey by the Polar-Orbiting Geophysical Observatories OGO 2 and OGO 4 1965-1967, Goddard Space Flight Center, *Report X-612-68-502*, Greenbelt, Maryland, 1968.

POGO (8/69) Model Coefficients 1970

J. C. Cain
(See address above.)

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 240 coefficients of the POGO (8/69) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1960.0 and extend up to degree and order 10 in the constant and first derivative terms. POGO (8/69) continues the series of POGO models, using OGO 2, 4, and 6 satellite data up to May 1968. Improvements over the earlier POGO models result from the extended data base and from a more careful selection of magnetically quiet periods.

Availability: On one tape, SPAN (NSSDC ID **#MG-18A**)

References:

J. C. Cain and R. E. Sweeney, Magnetic Field Mapping of the Inner Magnetosphere, *J. Geophys. Res.* 75, 4360, 1970.

POGO (8/71) Model Coefficients 1974

R. A. Langel
NASA/GSFC, Code 622
Greenbelt, Maryland 20771
SPAN: LTP::GEOLAN

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 240 coefficients of the POGO (8/71) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1960.0 and extend up to degree and order 10 in the constant and first derivative terms. This is the last in the series of POGO models. It considers field strength data for magnetically quiet conditions through the lifetimes of OGO 2, OGO 4, and OGO 6 (10/65-3/70). In total, more than 50,000 satellite measurements formed the basis for POGO (8/71).

Mead (1979) compared several models including POGO (8/71), AWC (75), IGS (75), and IGRF 1975 with observatory data for the time period 1970 through 1976. POGO (8/71), AWC (75), and IGS (75) showed equally good agreement, whereas IGRF 1975 exhibited a significantly poorer prediction ability. The good results with POGO (8/71) are particularly surprising because only scalar data (field strength) for a restricted time period were used to construct this model, whereas the others are based on much longer data records of scalar and vector data.

Availability: On one tape, SPAN (NSSDC ID **#MG-19A**)

References:

R. A. Langel, Near-Earth Disturbances in Total Field at High Latitudes: 1. Summary of Data from OGO 2, 4, and 6, *J. Geophys. Res.* 79, 2363, 1974.

G. D. Mead, An Evaluation of Recent Internal Magnetic Field Models, in: *Quantitative Modeling of Magnetospheric Processes*, W. P. Olson (ed.), 110-117, American Geophysical Union, Geophysical Monograph 21, Washington, D.C., 1979.

AWC (75) Model Coefficients 1976

N. W. Peddie and E. B. Fabiano
U. S. Geological Survey, Mail Stop 964
Denver Federal Center
Denver, Colorado 80225

Parameter: Earth's main (internal) magnetic field strength and vector

Brief Description: This data set contains the 248 coefficients of the AWC (75) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1975.0 and extend to degree and order 12 in the constant terms and to 8 in the first derivative terms. The U.S. Geological Survey (USGS) publishes an update of the main field and its secular variation every five years. This edition is based on approximately 100,000 surface, marine, and aeromagnetic measurements from 1939 through 1974 (see also POGO [8/71]).

Availability: On one tape, SPAN (NSSDC #**MG-1AA**)

References:

N. W. Peddie and E. B. Fabiano, A Model of the Geomagnetic Field for 1975 (AWC/75), *J. Geophys. Res.* 81, 2539, 1976.

IGS (75) Model Coefficients 1975

D. R. Barraclough
Institute of Geological Sciences
Edinburgh, United Kingdom

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 296 coefficients of the IGS (75) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1975.0 and extend to degree and order 12 in the constant terms, 8 in the first derivative terms, and 6 in the second derivative terms. The model is based on data from ground stations, aircraft flights, ocean surveys, and the OGO satellites (see also POGO [8/71]).

Availability: On tape, SPAN (NSSDC ID #**MG-1AB**)

References:

D. R. Barraclough, A Model of the Geomagnetic Field of Epoch 1975, *Geophys. J. Royal Astr. Soc.* 43, 645, 1975.

MGST (6/80) Model Coefficients

1980

R. A. Langel
NASA/GSFC, Code 622
Greenbelt, Maryland 20771
SPAN: LTP::GEOLAN

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 195 coefficients of the MGST (6/80) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1979.85 and extend to degree and order 13. No secular variation terms are included. This model was one of the first published results of the MAGSAT satellite mission. It is based on initial vector measurements for the magnetically quiet days of November 5-6, 1979. The authors included also statistically significant external terms of degree and order 1 describing the effect of external field sources.

Availability: On one tape, SPAN (NSSDC ID #**MG-1BA**)

References:

R. A. Langel, Initial Geomagnetic Field Model from MAGSAT, *NASA TM-80679*, Washington, D.C., 1980.

R. A. Langel, R. H. Estes, G. D. Mead, E. B. Fabiano, and E. R. Lancaster, Initial Geomagnetic Field Model from MAGSAT Vector Data, *Geophys. Res. Lett.* 7, 793, 1980.

MGST (4/81) Model Coefficients

1981

R. A. Langel
(See address above.)

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 258 coefficients of the MGST (4/81) spherical harmonics model of the Earth's main (core) magnetic field. The coefficients are for epoch 1980.0 and extend to degree and order 13 in the constant terms and 7 in the first derivative terms. This unpublished model is based on 15 days of MAGSAT data. Using the model for periods other than the actual MAGSAT flight period (1979-1980) is not recommended.

Availability: On one tape, SPAN (NSSDC ID #**MG-1BB**)

References:

R. A. Langel, J. Berbert, T. Jennings, and R. Horner, MAGSAT Data Processing: A Report for Investigators, pp. 45, 105, 106, *NASA TM-82160*, Washington, D.C., 1981.

GSFC (9/80) Field Model **1983**

R. A. Langel
NASA/GSFC, Code 622
Greenbelt, Maryland 20771
SPAN: LTP::GEOLAN

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set consists of the 462 coefficients for the GSFC (9/80) geomagnetic field model. The model is based on *(i)* 15,206 MAGSAT vector observations (November 5-6, 1979, same as used in MGST [6/80]), *(ii)* 71,000 OGO scalar observations (same as used in POGO [8/71] plus 24,000 additional data), *(iii)* measurements from 148 magnetic observatories, *(iv)* 300 marine measurements, *(v)* approximately 600 measurements from selected repeat stations. The coefficients are for epoch 1980.0 and extend to degree and order 13 in the constant and first derivative terms, 6 in the second derivative terms, and 4 in the third derivative terms. The time span of the data and of the model is 1960 through 1980. GSFC (9/80) constitutes a significant improvement over earlier models because of the enlarged data base and because the ground observations were corrected for crustal (anomaly) fields. Langel et al. (1982) compared GSFC (9/80) with MGST (6/80), AWC (75), and two other models. GSFC (9/80) shows a consistently closer agreement with the measurements than the other models over the whole 20-year time period. The software package includes a subroutine for calculation of the magnetic field strength and vector components.

Availability: On one tape, SPAN (NSSDC ID #**MG-12B**)

References:

R. A. Langel, R. H. Estes, and G. D. Mead, Some New Methods in Geomagnetic Field Modeling Applied to the 1960-1980 Epoch, *J. Geomag. Geoelectr.* 34, 327, 1983.

GSFC (12/83) Field Model **1985**

R. A. Langel
(See address above.)

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 367 coefficients of the GSFC (12/83) geomagnetic field model. The coefficients are for epoch 1980.0 and extend to degree and order 14 in the constant terms and 11 in the first derivative terms. The model is based on 54,728 MAGSAT data from November 1979 through April 1980 and on data from 91 magnetic observatories for 1978 through 1982. Different from earlier MAGSAT-based models, MAGSAT vector data are only used equatorward of 50° geomagnetic latitude to avoid the effects of field-aligned currents. Poleward of 50°, only field magnitude (scalar) data are considered. Again, as for GSFC (9/80), the observatory data are corrected for crustal (anomaly) biases. The authors also provide first order external coefficients and their dependence on the magnetic disturbance index *Dst*. The main field terms truncated to degree 10 were adopted as the definitive IGRF for epoch 1980. GSFC (12/83) was also used to derive the definitive IGRF models for 1945, 1950, 1955, and 1960 (see International Geomagnetic Reference Field). A subroutine for calculation of geomagnetic field strength and vector components is included.

Availability: On one tape, SPAN (NSSDC #**MG-12D**)

References:

R. A. Langel and R. H. Estes, The Near-Earth Magnetic Field at 1980 Determined from MAGSAT Data, *J. Geophys. Res.* 90, 2495, 1985.

USGS Model Coefficients for Continental U.S. and Hawaii 1985

N. W. Peddie
Denver Federal Center, Mail Stop 964
U. S. Geological Survey
Denver, Colorado 80225

Parameter: Geomagnetic field parameters for the continental U.S. and Hawaii

Brief Description: These models were developed at the U.S. Geological Survey (USGS) and describe the direction and intensity of the magnetic field in the United States at the beginning of 1985 and the rate of change expected for the next years. The models were derived from several tens of thousands of original field measurements from land, marine, and aerial surveys; from values synthesized with the International Geomagnetic Reference Field (IGRF) for 1985; and from recent data from magnetic observatories and repeat stations. The models are in the form of a spherical harmonics series up to degree and order 4 (24 coefficients) for the continental states and of degree and order 2 (eight coefficients) for Hawaii. Computation of geomagnetic field values is part of the USGS Online Information System, which can be accessed from a remote terminal.

Availability: On line at USGS; can be accessed via the toll free number (800) 358-2663 ([303] 279-2062 in Colorado); modem should be for 300 or 1200 baud (full duplex, no parity).

IGRF 1945-1980 Model Coefficients 1988

R. A. Langel, D. R. Barraclough
NASA/GSFC, Code 622
Greenbelt, Maryland 20771
SPAN: LTP::GEOLAN

Parameter: Earth's main magnetic field strength and vector

Brief Description: The International Geomagnetic Reference Field (IGRF) includes a series of spherical harmonics coefficients sets for different epochs. Revisions are made under the auspices of Working Group 1 of the International Association of Geomagnetism and Aeronomy (IAGA). The 1987 edition of IGRF includes ten spherical harmonics models. Nine describe the main field at epochs five years apart from 1945 to 1985 (degree and order 10), and the tenth describes the predicted secular variation of the field for the interval 1985-1990 (degree and order 8). Within the five-year intervals from 1945 to 1985 linear interpolation is recommended. The IGRF models are the result of the collaboration of mainly five groups: the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) in Moscow, U.S.S.R.; the National Aeronautics and Space Administration (NASA) in Greenbelt, Maryland, U.S.A.; the U.S. Geological Survey (USGS); the U.S. Naval Oceanographic Office (USNOO); and the British Geological Survey (BGS) in Edinburgh, United Kingdom. The IGRF models are the mean of the models published periodically by these agencies. IGRF 1985 and 1985-1990 are based on the BGS (Quinn et al., 1987; Barraclough and Kerridge, 1987), IZMIRAN (Golovkov and Kolomiitseva, 1987), and USGS (Peddie and Zunde, 1987) models. IGRF 1945, 1950, 1955, 1960, and 1980 were determined primarily from the GSFC (12/83) model (Langel et al., 1988). IGRF 1965, 1970, 1975, and 1980 are weighted means of the NASA, IGS, and USGS models (Peddie, 1982). The IGRF models for 1945 through 1980 are definitive models (DGRFs) in the sense that no further revisions are planned for these models.

Availability: On one tape, one diskette, SPAN (These coefficients are included in the BILCAL/IGRF package.) (NSSDC ID **#PG-18C**)

References:

N. W. Peddie, International Geomagnetic Reference Field: The Third Generation, *J. Geomagn. Geoelectr.* 34, 309, 1982.

D. R. Barraclough, International Geomagnetic Reference Field: The Fourth Generation, *Phys. Earth Planet. Inter.* 48, 279, 1987.

J. M. Quinn, D. J. Kerridge, and D. R. Barraclough, IGRF Candidates for 1980 and 1985, *Phys. Earth Planet. Inter.* 48, 313, 1987.

V. P. Golovkov and G. I. Kolomiitseva, Models of Secular Geomagnetic Variations for 1980-1990, *Phys. Earth Planet. Inter.* 48, 320, 1987.

N. W. Peddie and A. K. Zunde, A Model of Geomagnetic Secular Variations for 1980-1983, *Phys. Earth Planet. Inter.* 48, 324, 1987.

D. R. Barraclough and D. J. Kerridge, BGS Candidate Models for the 1985 Revision of the International Geomagnetic Reference Field, *Phys. Earth Planet. Inter.* 48, 306, 1987.

R. A. Langel, D. R. Barraclough, D. J. Kerridge, V. P. Golovkov, T. J. Sabaka, and R. H. Estes, Definitive IGRF Models for 1945, 1950, 1955, and 1960, J. *Geomagn. Geoelectr.* 40, 645, 1988.

International Geomagnetic Reference Field, Revision 1987, *J. Geomag. Geoelectr.*, 39, 773-779, 1987, and EOS, *AGU Transactions*, 69, 559, 1988.

GSFC (11/87) Model Coefficients 1988

R. A. Langel
(See address above.)

Parameter: Earth's main magnetic field strength and vector

Brief Description: This data set contains the 448 coefficients of the GSFC (11/87) geomagnetic field model. The spherical harmonics series is of degree and order 13 in the constant and first derivative terms. GSFC (11/87) is the first model making use of the large DE data base. Data from the DE 2 spacecraft for September 30, 1981, through January 6, 1983, are combined with data from MAGSAT (11/79-4/80), from Project MAGNET (1981-1983), from 158 magnetic observatories (1979-1983), from marine surveys (1980-1983.5), and from land surveys (1979.5-1983.5). Vector data were obtained from MAGSAT and MAGNET (aircraft: 1.5 km to 8 km). From all other data sources only scalar data were considered. Poleward of 50° latitude, only scalar data were used from MAGSAT to avoid the contribution from the field-aligned currents in the polar ionosphere. For all observatory data the anomaly biases from non-core fields were taken into account. The GSFC (11/87) model is virtually identical to the GSFC (12/83) model at 1980 and may be regarded as an extension of that model in time to 1983.5. Its mean epoch is 1982. The model differs significantly from the IGRF model. Langel et al. (1988) also determined the first degree coefficients resulting from external sources and their dependence on the magnetic disturbance index *Dst*. The software package includes a subroutine for calculation of magnetic field strength and vector components.

Availability: On one tape, SPAN (NSSDC ID #**MG-12C**)

References:

R. A. Langel, J. R. Ridgway, M. Sugiura, and K. Maezawa, The Geomagnetic Field at 1982 from DE 2 and Other Magnetic Field Data, *J. Geomag. Geoelectr.* 40, 1103, 1988.

MDTILT Magnetic Field Model 1969

W. P. Olson
McDonnell Douglas Company
Code A3-208, Mail Stop 13/3
5301 Bolsa Avenue
Huntington Beach, California 92647

Parameter: Earth's magnetic field vector and strength including external sources

Brief Description: This analytic model considers contributions from the magnetopause and tail currents. It was created by solving the pressure balance equation at the magnetopause using the Earth's dipole and the magnetopause surface current as sources for the total magnetic field. Tail currents are determined empirically by comparing the model to actual spacecraft data. The effect of variable solar wind pressure is incorporated by using the magnetopause standoff distance. The field is determined by Legendre polynomial expansions, and magnetic field values are given in solar magnetospheric coordinates. The model is recommended for geocentric distances out to about seven Earth radii. The usefulness of this older model is limited by the fact that it does not consider the magnetic field contribution caused by the ring current.

Availability: On one magnetic tape as provided by the author (NSSDC ID #**MG-22A**)

References:

W. P. Olson, The Shape of the Tilted Magnetosphere, *J. Geophys. Res.* 74, 5642, 1969.

Olson-Pfitzer Field Model 1974

K. A. Pfitzer, W. P. Olson
(See address above.)

Parameter: Earth's magnetic field vector and strength including external sources

Brief Description: This is an analytical model of the Earth's magnetic field valid from the dayside subsolar magnetosphere to beyond lunar orbit in the nightside magnetotail. Only the quiet time magnetosphere is represented including the contributions from magnetopause, tail, and ring currents. The internal (core) field is represented by a fixed dipole. The field representation is given in Cartesian GMS coordinates using sixth-order expansions of power series and exponential terms. The 180 coefficients were determined by fitting to over 600 magnetometer measurements from OGO 3 and 5. Shortcomings of this model are the restriction to quiet conditions and the fact that the direction of the main dipole and the ring current is fixed (i.e., perpendicular to the Earth-Sun direction).

Availability: On one magnetic tape (NSSDC ID #**MG-23A**). A more recent, unpublished version is available from the authors in computer form.

References:

W. P. Olson and K. A. Pfitzer, A Quantitative Model of the Magnetospheric Magnetic Field, *J. Geophys. Res.* 79, 3739, 1974.

W. P. Olson (ed.), *Quantitative Modeling of Magnetospheric Processes*, American Geophysical Union, Washington, D.C., 1979.

Mead-Fairfield Field Model 1975

D. H. Fairfield
NASA/GSFC, Code 695
Greenbelt, Maryland 20771
SPAN: LEPVAX::U2DHF

Parameter: Earth's magnetic field direction and intensity out to 17 Earth radii

Brief Description: For this tilt dependent model, four sets of model coefficients are available for four levels of magnetic activity as parameterized by *Kp*. It is valid out to 17 Earth radii. The model is expressed as second order power series expansions in solar magnetic coordinates, quadratic in position and linear in tilt. Model coefficients (17) were obtained by a least-square-fit to 12,616 vector field measurements from 451 orbits of four IMP satellites between 1966 and 1972. The effect of localized current systems like the ring current and sheet currents in the tail are not particularly well modeled by these quadratic expansions. The program includes the GSFC (12/66) main field model for the representation of the internal (core) part of Earth's total magnetic field. A simple offset dipole field can be chosen instead of the spherical harmonics GSFC model, to reduce the computation time.

Availability: On tape and SPAN (NSSDC ID #**MG-21A**). Also available is the data base used in constructing the model (NSSDC ID #**MG-21B**).

References:

D. H. Fairfield and G. D. Mead, Magnetospheric Mapping with a Quantitative Geomagnetic Field Model, *J. Geophys. Res.* 80, 535, 1975.

Geotail Field Model 1979

D. B. Beard
Department of Physics and Astronomy
University of Kansas
Lawrence, Kansas 66045

Parameter: Earth's magnetic field vector and strength including external sources

Brief Description: This data set consists of a set of subroutines designed to calculate the magnetic field of the Earth from -40 Earth radii to +10 Earth radii. The coefficients are calculated assuming the axis of the Earth's dipole is perpendicular to the Earth-Sun line. The magnetic potential was obtained by integrating over a model magnetotail current system and fitting the surface field to a set of Bessel functions.

Availability: On one tape as provided by author (NSSDC ID # **MG-24A**)

References:

D. B. Beard, The Magnetotail Magnetic Field, *J. Geophys. Res.* 84, 2118, 1979.

Tsyganenko Magnetic Field Model (Related Software) 1987

N. A. Tsyganenko
Institute of Physics
Leningrad State University
Leningrad 198904
U.S.S.R.

Parameter: Earth's magnetic field (strength and vector) out to 70 Earth radii

Brief Description: This software package contains (1) the semi-empirical model of the magnetospheric magnetic field developed by Tsyganenko (1987), (2) the third generation of the International Geomagnetic Reference Field (IGRF) model 1965 to 1990 for the inner dipole-like part of the geomagnetic field, and (3) programs for field-line tracing and coordinate transformations.

The 1987 Tsyganenko model is based on IMP-A, -B, -C, -D, -E, -F, -G, -H, -I, -J, and HEOS 1, 2 measurements over the time period 1966 to 1980, using a total of 36,682 data points. It describes the magnetic field from about four to 70 Earth radii for several levels of magnetic disturbance. It includes a tilted geodipole and the contributions from external magnetospheric sources: (1) the field of the ring current, (2) the magnetotail current system, (3) the remaining part of the total external field including the field of magnetopause currents and an averaged contribution from the large-scale system of field-aligned currents. Two versions were established, a "long" version with 26 parameters and six disturbance levels, valid up to 70 Earth radii, and a "short" version with 20 parameters and eight disturbance levels, valid up to 30 Earth radii. Improvements of the 1987 Tsyganenko model have been proposed by Stern (1988) and Tsyganenko (1989).

The software package available from the National Space Science Data Center (NSSDC) was provided by V. A. Pilipenko, Institute of the Physics of the Earth, B. Gruzinskayz, 10, Moscow, 123810, U.S.S.R.. It includes (1) an interactive driver program developed at NSSDC to compute the main and the magnetospheric parts of the geomagnetic field at arbitrary points (GSM or GEO coordinates) in the near-Earth space (up to 70 Earth radii) for given year, day of year, universal time, and magnetic disturbance level (*Kp*); (2) the subroutines and functions; (3) a program to compute dipole and corrected geomagnetic coordinates from various coordinate systems; (4) a program to compute the distance between two points on the geosphere; (5) a program to calculate the field-aligned projection of a given point in space onto the Earth's surface; (6) a test program; and (7) the output from this program.

Availability: On one tape, one diskette (for use on PCs), SPAN (NSSDC ID **#PG-18D**). The predecessor model by Tsyganenko and Usmanov (1982) is also available from NSSDC (NSSDC ID **#MG-25A**, one tape). The Tsyganenko 1989 model is now also available on one diskette (NSSDC ID **#PG-18E**).

References:

C. T. Russell, Geophysical Coordinate Transformations, *Cosmic Electrodynamics*, Volume 2, 184-196, 1971.

N. W. Peddie, A Third Generation of International Geomagnetic Reference Field Models, *J. Geomag. Geoelectr.* 34, 310-320, 1982.

N. A. Tsyganenko, A. V. Usmanov, Determination of the Magnetospheric Current System Parameters and Development of Experimental Geomagnetic Field Models Based on Data from IMP and HEOS Satellites, *Planet. Space Sci.* 30, 985-998, 1982.

N. A. Tsyganenko, A. V. Usmanov, V. O. Papitashvili, N. E. Papitashvili, V. A. Popov, Software for Computations of Geomagnetic Field and Related Coordinate Systems, Soviet Geophysical Committee, *Special Report*, 58 pp., Moscow, 1987.

N. A. Tsyganenko, Global Quantitative Models of the Geomagnetic Field in the Cislunar Magnetosphere for Different Disturbance Levels, *Planet. Space Sci.* 35, 1347-1358, 1987.

D. Stern, personal communication, 1988. (For more information, contact D. Stern, NASA/GSFC, Code 695; telephone: (301) 286-8292; SPAN: LEPVAX::U5DPS.)

N. A. Tsyganenko, A Magnetospheric Magnetic Field Model with a Wrapped Tail Current Sheet, *Planet. Space Sci.* 37, 5-20, 1989.

FIELD/FIELDG 1968

J. C. Cain
Department of Geology
Florida State University
Tallahassee, Florida 32306-3026
(904) 644-4014

Parameter: Computation of magnetic field parameters from spherical harmonics coefficients

Brief Description: The program calculates the Earth's magnetic field components at a given point in space and time from a spherical harmonic expansion of the main (core) field. The program accepts geodetic or geocentric coordinates and accommodates Gauss-normalized as well as Schmidt-normalized coefficients. In a first step the coefficients are determined for the time in decimal years required by the user. In its present form the package includes the coefficients of the IGRF (10/68) model, which is of degree and order 8 in its constant and first derivative term (epoch 1965, oblateness considered). But other sets of spherical harmonics coefficients can be easily adopted for use with FIELDG.

Availability: On one tape (NSSDC ID #**PG-11A**)

References:

J. C. Cain, S. Hendricks, W. E. Daniels, and D. C. Jensen, Computation of the Main Geomagnetic Field from Spherical Harmonic Expansions, National Space Science Data Center, *Report 68-11*, Greenbelt, Maryland, 1968. (Revised version of *NASA-TM-X-611-64-316*, 1964) (B01411)

INVAR/NEWMAG 1967

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University of California, San Diego
CASS C-011
La Jolla, California 92093
SPAN: CASS::CARL

Parameter: Computation of magnetic field parameters and *L*-value from spherical harmonics coefficients

Brief Description: This package includes the subroutine INVAR to calculate *L*-values at any specified point in space (geocentric coordinates) and NEWMAG to calculate the vector components of the Earth's main (core) magnetic field as given by the GSFC (9/65) model. Subroutine INTEG determines the value of the integral invariant *I* by numerically integrating along the field line from the specified point of interest to its conjugate point. An input accuracy parameter controls the number of points (maximum: 200) used in the integration. CARMEL computes the shell parameter *L* from *I* and *B* by using McIlwain's (1961) formulas. These programs should be used only for the time range 1960-1965 for which the GSFC (9/65) is considered valid. The package was designed for card deck operation on an IBM 7094 and 360 mainframe. Hilberg (1971) compared *L*-values calculated with INVAR, SHELLG, and INTELG (see "FELDG, SHELLG, INTELG," page 4-19.)

Availability: On one tape (NSSDC ID #**PG-16A**)

References:

C. E. McIlwain, Coordinates for Mapping the Distribution of Magnetically Trapped Particles, *J. Geophys. Res.* 66, 3681, 1961.

A. Hassitt and C. E. McIlwain, *Computer Programs for the Computation of B and L*, NSSDC 67-27, Greenbelt, Maryland, 1967. (B17336)

ALLMAG/INVARA/LINTRA 1972

E. G. Stassinopoulos
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
(301) 286-8067

Parameter: Computation of magnetic field parameters and *L*-value from spherical harmonics model coefficients; field-line tracing

Brief Description: This package includes the programs ALLMAG for calculating geomagnetic vector components, INVARA for calculating *L*-values, and LINTRA for field-line tracing, all designed and tested by Stassinopoulos and Mead (1972). These subroutines operate with the usual spherical harmonics representation of the Earth's main (core) magnetic field. Seven sets of coefficients are included in the code: GSFC (9/65), GSFC (12/66), POGO (10/68), POGO (8/69), IGRF 1965, Leaton et al. (1965), and Hurwitz (1970). ALLMAG is equivalent to Cain's FIELDG program, with the added flexibility of the choice of seven models. INVARA is a version of McIlwain's INVAR subroutine adopted for use with the ALLMAG field calculation subroutine. LINTRA traces field lines from any point in space to a specified altitude in the same or opposite hemisphere, using any of the models contained in ALLMAG.

The modified ALLMAG versions ONEMAG (#**PG-12C, D**) and DEKMAG (#**PG-12E**) are also available from NSSDC. ONEMAG contains built-in coefficients for only one field model, namely IGRF 1965 (#**PG-12D**) or IGRF 1980 (#**PG-12C**). DEKMAG reads in coefficients, rather than having built-in coefficients (as DATA statement). All programs were designed for card deck operation on an IBM 360/91 mainframe.

Availability: On one tape (NSSDC ID #**PG-12A**)

References:

B. R. Leaton, S. R. C. Malin, and M. J. Evans, An Analytical Representation of the Estimated Geomagnetic Field and Its Secular Change for the Epoch 1965.0, *J. Geomag. Geoelectr.* 17, 187, 1965.

E. G. Stassinopoulos, Computer Codes for Geomagnetic Field-Line Tracing and Conjugate Intersect Calculations, GSFC, *Report X-642-68-429*, 1968. (B09143)

L. Hurwitz, *Mathematical Model of the 1970 Geomagnetic Field*, ESSA Coast and Geodetic Survey, May 4, 1970.

E. G. Stassinopoulos, and G. D. Mead, ALLMAG, GDALMG, LINTRA: Computer Programs for Geomagnetic Field and Field-Line Calculations, National Space Science Data Center, *Report 72-12*, Greenbelt, Maryland 1972. (B11996)

G. Kluge
ESA/European Space Operations Centre
Robert-Bosch-Str. 5
6100 Darmstadt
Federal Republic of Germany

Parameter: Calculation of geomagnetic field parameters and *L*-value from spherical harmonics coefficients

Brief Description: This software package contains the FORTRAN subroutine FELDG to calculate magnetic field components and the subroutines SHELLG and INTELG to calculate McIlwain's *L* parameter. By using a polynomial representation of the geomagnetic potential with inverse Cartesian coordinates, the algorithm for the field computation is considerably simplified and can easily be extended to obtain spatial derivatives of higher order. FELDG can be used with Gauss-normalized as well as Schmidt-normalized magnetic field coefficients for any of the internal source field models. SHELLG determines McIlwain's *L*-value by integrating along the magnetic field line to the conjugate point. The advantage of using the inverse coordinates system is a significant reduction in the number of steps needed to evaluate the integral invariant. The INTELG makes use of a precalculated (with SHELLG) tabulation of *L*-values for a specific magnetic field model. *L* is determinate by interpolation and Fourier expansion from this table. Such a procedure reduces the computation time for *L* considerably. Kluge (1970) reports a root-mean-square error of about 0.05% for *L*-values up to ten. Pre-calculated *L*-tables are, however, available only for the IGRF 1965, GSFC (12/66), and POGO (10/68) magnetic field models. Hilberg (1971) compared the *L*-values calculated with INVAR, SHELLG, and INTELG for a wide range of latitudes, longitudes, and altitudes. He found differences up to 5%, with the INVAR *L*-values always exceeding the other two calculations. The study also notes artificial discontinuities in the longitudinal variation of *L*-values obtained with INVAR. The average execution time for *B* and *L* calculation of INVAR, SHELLG, and INTELG is 70, 46, and 12 msec.

Availability: On one tape (NSSDC ID #**PG-13A**) (FELDG and SHELLG are included in the BILCAL/IGRF package.)

References:

G. Kluge, A Generalized Method for the Calculation of the Geomagnetic Field from Multipole Expansions, European Space Operations Centre, *ESOC Internal Note No. 61*, Darmstadt, 1970.

G. Kluge, Computer Program SHELL for the Calculation of *B* and *L* from Models of the Geomagnetic Field, *ESOC Internal Note No. 67*, Darmstadt, 1970. (B20244)

G. Kluge, Computation of the Magnetic Shell Parameter *L* from a Compressed Data Table, *ESOC Internal Note No. 72*, Darmstadt, 1970.

G. Kluge, Direct Computation of the Magnetic Shell Parameter, *Comp. Phys. Comm.* 3, 31, 1972.

G. Kluge and K. G. Lenhart, Numerical Fits for the Geomagnetic Shell Parameter, *Comp. Phys. Comm.* 3, 36, 1972.

R. H. Hilberg, Magnetic Shell Parameter Calculations, KMS Industries, *Report KMS 71-02*, 1971 (Available from NSSDC on one microfiche, #**PG-21A**).

NEWBL 1977

K. A. Pfitzer
McDonnell Douglas Astronautics Corporation
Code A3-365, Mail Stop 13/3
5301 Bolsa Avenue
Huntington Beach, California 92647

Parameter: Earth's main magnetic field; contributions from external sources; *L*-value

Brief Description: This package consists of the main subroutine FLDINT and several supporting subroutines. For a given point in space FLDINT determines the magnetic field strength (main and external contributions), the *L*-value, the minimum field strength along the field line, and the electron drift velocity. The IGS (75) model is used for the internal (core) field and the Olson-Pfitzer model for the external source fields. *L*-values are obtained by the usual integration procedure along the magnetic field line from mirror point to conjugate mirror point. Different from other *L* calculation programs, however, FLDINT can modify the mirror points to more accurately represent drift shells of isotropic particle distribution in the drift shell splitting region. The program also flags open field lines inside the auroral oval. This is an excellently documented software package that is easy to adjust to special applications.

Availability: On one tape (NSSDC ID **#PG-18A**)

TRAJLST 1985

Request Coordination
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
SPAN: NCF::REQUEST

Parameter: Field-line tracing

Brief Description: This program is used by the National Space Science Data Center's Satellite Situation Center (SSC) for magnetic field-line tracing. The main geomagnetic field is represented by a spherical harmonics model (IGRF 65 or 75) and the external field by the Mead-Fairfield model. Required input information includes time, year, altitude where trace should stop, latitude, longitude, and altitude where trace should start (e.g., satellite location). TRAJLST is adopted to the special needs of the SSC. The source code is, unfortunately, poorly documented, which may hinder use of the program for other applications.

Availability: On tape (NSSDC ID **#PG-18B**)

D. Bilitza
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
(301) 286-9536 SPAN: NCF::BILITZA

Parameter: Earth's main magnetic field (magnitude, vector components, declination, inclination); *L*-value; field strength at magnetic equator

Brief Description: This software package contains the International Geomagnetic Reference Field (IGRF) from 1945 to 1985 (see "IGRF 1945-1985 Model Coefficients," page 4-11), the field calculation subroutine FELDG, and the *L*-shell calculation subroutine SHELLG (see "FELDG/SHELLG/INTELG," page 4-19). The IGRF models represent the Earth's main field without external sources. They use a spherical harmonics expansion of the scalar potential in geocentric coordinates.

The NSSDC program BILCAL produces tables of geomagnetic field strength and vector, declination, inclination, dipole moment, *L*-value, and field strength at the magnetic equator. As a variable, one can choose latitude, longitude (geodetic), altitude, or year (1945-1990).

The subroutines FELDG and SHELLG were developed by Kluge (1972) at the European Space Operations Centre (ESOC). His field (FELDG) and *L* calculation (SHELLG) uses inverse Cartesian coordinates. This method simplifies the *B* and *L* computation and reduces the required computer time by a factor of 10 in comparison with earlier calculation schemes. Kluge's SHELLG was corrected so that it now takes account of the secular changes in magnetic dipole moment.

Availability: On one tape, one diskette (for use on PCs), SPAN, NSSDC's NODIS account (NSSDC ID #**PG-18C**)

References:

G. Kluge, Direct Computation of the Magnetic Shell Parameter, *Comp. Phys. Comm.*, 3, 31-35, 1972.

AE/AP Trapped Particle Flux Maps — 1966-1980

J. I. Vette
NASA/GSFC, Code 933
Greenbelt, Maryland 20771

Parameter: Trapped electron and proton fluxes in Earth's radiation belt

Brief Description: These maps contain omnidirectional, integral electron (AE maps) and proton (AP maps) fluxes in the energy range 0.04 MeV to 7 MeV for electrons and 0.1 MeV to 400 MeV for protons in the Earth's radiation belt (L = 1.2 to 11 for electrons, L = 1.17 to 7 for protons). The fluxes are stored as functions of energy, L-value, and B/B_0 (magnetic field strength normalized to its equatorial [minimum] value on the field line). The maps are based on data from more than 20 satellites from the early sixties to the mid-seventies. AE-8 and AP-8 are the latest editions in a series of updates starting with AE-1 and AP-1 in 1966. The progress in modeling the trapped particle population is documented in several reports as indicated in the tables below. Included in these reports are (1) a description of model map development, (2) tables and graphs of fluxes, and (3) results from flux integrating along selected (mostly circular) orbits. The different electron models AE can be distinguished as inner (L = 1.2-3) or outer (L = 3-11) zone models and as models for solar cycle maximum or minimum conditions. AE-8 is the first model that covers the whole L range and both solar cycle extrema. The AP maps differ in energy range and solar cycle phase. AP-8 is the first model for the whole energy range and both solar cycle extrema.

None of the flux maps consider time variations beyond the solar cycle minimum/maximum distinction. In the AE-5 report for inner zone electrons, the three dominant time effects were investigated: (1) Magnetic storms strongly affect electrons with energies higher than 0.7 MeV at higher L-shells; (2) the Starfish nuclear explosion of July 9, 1962, increased electrons on low L-shells with intermediate energy (about 1 MeV); (3) the solar cycle effect is most significant for electrons with energies below 0.7 MeV. Magnetic storm effects are not yet included in any of the AE maps. For AE-5 1975 Projected and AE-6, the Starfish residue was subtracted. AE-8 is a synthesis of AE-5 Projected, AE-6, AE-4, and new data from the OV3 3, OV1 19, Azur, and ATS 6 satellites. In the outer zone, because of large temporal variations, averages were taken over long intervals (six months or more). The AE-3, AE-4, and AE-8 reports also include local time functions down to L = 3; however, these were not included in the computer code. AE-3, the model for the region of geostationary (geosynchronous) satellites, provides also tools for radiation exposure assessment. AE-1, AE-2, and AE-5 include both omni- and unidirectional flux maps.

The largest errors occur where steep gradients in spatial and spectral distribution exist and where time variations are not well understood. A widely quoted error estimate is "a factor of 2." An even larger error must be considered for differential fluxes (in angle or energy) created from the omnidirectional, integral flux maps. It should be noted that the Jensen-Cain magnetic field model (see page 4-4) with epoch 1960.0 was used throughout the period when trapped radiation data was collected for all AE/AP models. Therefore, one has to be careful in extrapolating these models to later epochs. It is recommended that the map-specific epochs as listed in the tables below be used for all applications of the models.

Availability: Each model map is available on one tape, generated on IBM 7094, for use in conjunction with program MODEL. AE-8, AP-8 are part of the RADBELT package. The reports are available on microfiche (please order by B number). (NSSDC ID **#MT-11 to -18**, **#MT-21 to -28**, **#MT-2A**, see tables below)

Name	Energy Range MeV	*L* Range	Solar Cycle Condition	Epoch	Reference	NSSDC ID on Tape
AE-1	0.30 - 7	1.2	minimum	7/63	Vette (1966)	**MT-21B**
* AE-2	0.04 - 7	1.2 - 6.3	minimum	8/64	Vette et al. (1966)	**MT-22B**
AE-3	0.01 - 6	6.6			Vette and Lucero (1967)	**MT-23A***
AE-4	0.04 - 4.85	3 - 11	min. & max.	64 & 67	Singley and Vette (1972a, b)	**MT-24B**
AE-5	0.04 - 4	1.2 - 2.8	maximum	10/67	Teague and Vette (1972a, b)	**MT-25B**
1975 Proj.	0.04 - 4	1.2 - 2.8	minimum	1975	Teague and Vette (1974)	**MT-26D†**
AE-6	0.04 - 4	1.2 - 2.8	maximum	1980	Teague et al. (1976)	**MT-28B**
AE-8	0.04 - 7	1.2 - 11	minimum maximum	1975 1980	Vette (1989)	**MT-2AA** **MT-2AB**

* Only on microfiche.
† Tape includes outer zone solar minimum map AE-4.

Name	Energy Range MeV	*L* Range	Solar Cycle Condition	Epoch	Reference	NSSDC ID on Tape
AP-1	30 - 50	1.2 - 2.9	minimum	9/63	Vette (1966)	**MT-11B**
AP-2	15 - 30	1.2 - 3.1	minimum	9/63	Vette (1966)	**MT-12B**
AP-3	> 50	1.2 - 2.9	minimum	9/63	Vette (1966)	**MT-13B**
AP-4	4 - 15	1.2 - 4.2	minimum	9/63	Vette (1966)	**MT-14B**
AP-5	0.1 - 4	1.2 - 6.6			King (1967)	**MT-15B**
AP-6	4 - 30	1.2 - 4			Lavine and Vette (1969)	**MT-16B**
AP-7	> 50	1.15 - 3	maximum	1/69	Lavine and Vette (1970)	**MT-17B**
AE-8	0.1 - 400	1.17 - 7	minimum maximum	1964 1970	Sawyer and Vette (1976)	**MT-18B*** **MT-18C***

* A compressed version of the AP-8 maps is available for solar minimum (**MT-18F**) and maximum (**MT-18H**).

References:

J. I. Vette, Models of the Trapped Radiation Environment, Volume I: Inner Zone Protons and Electrons (AE-1, AP-1, AP-2, AP-3, AP-4), National Aeronautics and Space Administration, *NASA SP-3024*, Washington, D.C., 1966. (B01302)

J. I. Vette, A. B. Lucero, and J. A. Wright, Models of the Trapped Radiation Environment, Volume II: Inner and Outer Zone Electrons (AE-2), *NASA SP-3024*, Washington, D.C., 1966. (B01302)

J. I. Vette and A. B. Lucero, Models of the Trapped Radiation Environment, Volume III: Electrons at Synchronous Altitudes (AE-3), *NASA SP-3024*, Washington, D.C., 1967. (B01302)

J. H. King, Models of the Trapped Radiation Environment, Volume IV: Low Energy Protons (AP-5), *NASA SP-3024*, Washington, D.C., 1967. (B01305)

J. P. Lavine and J. I. Vette, Models of the Trapped Radiation Environment, Volume V: Inner Belt Protons (AP-6), *NASA SP-3024*, Washington, D.C., 1969. (B06823)

J. P. Lavine and J. I. Vette, Models of the Trapped Radiation Environment, Volume VI: High Energy Protons (AP-7), *NASA SP-3024*, Washington, D.C., 1970. (B06822)

W. L. Imhof, C. O. Bostrom, D. S. Beall, J. C. Armstrong, H. H. Heckman, P. J. Lindstrom, G. H. Nakano, G. A. Paulikas, and J. B. Blake, Models of the Trapped Radiation Environment, Volume VII: Long Term Time Variations, *NASA SP-3024*, Washington, D.C., 1971. (B01302)

G. W. Singley and J. I. Vette, *The AE-4 Model of the Outer Radiation Zone Electron Environment*, NSSDC 72-06, Greenbelt, Maryland, 1972. (B17797)

G. W. Singley and J. I. Vette, *A Model Environment for Outer Zone Electrons*, NSSDC 72-13, Greenbelt, Maryland, 1972. (B14862)

M. J. Teague and J. I. Vette, *The Inner Zone Electron Model AE-5*, NSSDC 72-10, Greenbelt, Maryland, 1972a. (B14860)

M. J. Teague and J. I. Vette, *The Use of the Inner Zone Electron Model AE-5 and Associated Computer Programs*, NSSDC 72-11, Greenbelt, Maryland, 1972b. (B14752)

R. H. Hilberg, M. J. Teague, and J. I. Vette, *Comparison of the Trapped Electron Models AE-4 and AE-5 with AE-2 and AE-3*, NSSDC 74-13, Greenbelt, Maryland, 1974.

M. J. Teague and J. I. Vette, *A Model of the Trapped Electron Population for Solar Minimum (AE-5 1975 Projected)*, NSSDC 74-03, Greenbelt, Maryland, 1974. (B19648)

D. M. Sawyer and J. I. Vette, *Trapped Particle Environment for Solar Maximum and Solar Minimum (AP-8)*, NSSDC 76-06, Greenbelt, Maryland, 1976. (B28883)

M. J. Teague, K. W. Chan, and J. I. Vette, *AE-6: A Model Environment of Trapped Electrons for Solar Maximum*, NSSDC 76-04, Greenbelt, Maryland, 1976. (B26738)

J. I. Vette, K. W. Chan, and M. J. Teague, Problems in Modeling the Earth's Trapped Radiation Environment, Air Force Geophysics Laboratory, *Report AFGL-TR-78-0130*, Hanscom AFB, Massachusetts, 1978.

J. I. Vette, The AE-8 Model, pp. 4.19-4.28, in: Development of Improved Models of the Earth's Radiation Environment, Technical Note 1: Model Evaluation, European Space Agency, *ESTEC Contract No. 8011/88/NL/MAC*, Noordwijk, The Netherlands, 1989.

MODEL Program

1983

C. K. Chen
NASA/GSFC, NSSDC
Greenbelt, Maryland 20771

Parameter: Differential or integral, omnidirectional electron and proton fluxes in Earth's radiation belt

Brief Description: The program MODEL calculates the integral or differential fluxes of trapped electrons or protons in Earth's radiation belt by interpolating in one of the AE/AP trapped particle flux maps. The program expects an array of energies, *L*-values, and B/B_0 (magnetic field strength normalized to its equatorial [minimum] value on the field line) values and produces tables of fluxes for these conditions. The specific flux map should be added as BLOCKDATA statement at the end of the program. Fluxes are obtained by first applying a two-dimensional interpolation procedure to the logarithmic fluxes in $L \times B/B_0$ space and by then interpolating linearly with energy. Maps available in the BLOCK DATA format include AE-5, AE-6, AE-8, and AP-8.

Availability: On tape (NSSDC ID #**PT-11A**)

References:

M. J. Teague and J. I. Vette, *The Use of the Inner Zone Electron Model AE-5 and Associated Computer Programs*, NSSDC 72-11, Greenbelt, Maryland, 1972.

RADBELT 1988

D. Bilitza
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
(301) 286-9536 SPAN: NCF::BILITZA

Parameter: Omnidirectional, integral (or differential) electron or proton fluxes in Earth's radiation belt

Brief Description: This software package includes (1) an improved and updated version of the old MODEL program (MODEL87), (2) an interactive driver program (RADBELT), (3) the electron AE-8 and proton AP-8 flux maps for solar maximum and minimum, and (4) the interpolation subroutines. RADBELT and MODEL87 compute omnidirectional, integral, or differential (in energy) fluxes of electrons and protons trapped in Earth's radiation for specified energy, *L*-value, and B/B_0 range (B/B_0 is magnetic field strength normalized to the equatorial value). The fluxes are obtained by an interpolation procedure from the AE-8 and AP-8 trapped particle flux maps. The RADBELT program allows the user to specify input parameters and options on line and generates flux tables that can be stored for later use.

Availability: On one tape, two diskettes (for use on PCs), SPAN, NSSDC's NODIS account (NSSDC ID #**PT-11B**)

FLOUT Transformation 1971

D. M. Sawyer
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
SPAN: NCF::SAWYER

Parameter: Converts omnidirectional fluxes to unidirectional fluxes or vice versa

Brief Description: The Flux Omni Uni Transformations (FLOUT) program integrates over a set of unidirectional flux data to obtain omnidirectional flux, or, alternatively, differentiates omnidirectional flux data to obtain unidirectional flux. The input data is an array of flux values (either omni- or unidirectional) as a function of either magnetic field strength or the cosine of the equatorial pitch angle. A complete set of points is required spanning the region along the field line from the point of interest to the atmospheric cutoff.

Availability: On one microfiche (NSSDC ID #**PT-11C**)

References:

C. S. Roberts, On the Relationship Between the Unidirectional and Omnidirectional Flux of Trapped Particles on a Magnetic Line of Force, *J. Geophys, Res.* 70, 2517, 1965.

J. I. Vette, Models of the Trapped Radiation Environment, Volume I: Inner Zone Protons and Electrons, National Aeronautics and Space Administration, *NASA SP-3024*, Washington, D.C., 1966. (B01302)

D. M. Sawyer, Program (FLOUT), KMS Technology Center, *Special Report*, 1971.

NSSDC
Request Coordination
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
SPAN: NCF::REQUEST

Parameter: Trapped particle fluxes integrated along orbit

Brief Description: This data set consists of the orbit generating ORB program and the flux integrating ORP program. Both programs were written and tested for IBM 360 mainframe computers (last update in 1983, version 4.0). ORB uses a Brouwer (1959) and a Lyddane (1963) orbit generator; the latter is used for eccentricities smaller than 0.1. Kluge's INTEL subroutine is part of ORB for calculation of geomagnetic field strength *B* and *L*-value using the IGRF 1965 field model updated to epoch 1970. For given orbit characteristics (eccentricity, inclination, semi-major axis, perigee, and ascension) the program calculates longitude, latitude, altitude, *B* and *L* along the orbit and records them on magnetic tape. This tape can then be used as input for the ORP program which determines the orbital integrated particle fluxes. ORP calculates the electron or proton fluxes by interpolating in the AE-8 or AP-8 particle flux maps. Several different output tables can be generated with ORP including integrated flux and peak flux summaries. Teague and Vette (1974) discuss the accuracy of the orbit-accumulated fluxes and provide tables of the error estimates for different orbit times and time step sizes. It has been noted that neither the eccentricity nor the inclination should be set to a zero value. The eccentricity should not be smaller than 0.05. This software package is not recommended for low-altitude orbits where the orbit-accumulated fluxes are highly sensitive to small orbital changes, as a result of the steep gradients in the trapped particles models. At low Earth orbits (LEO) the dominant flux contributions are almost exclusively from the South Atlantic Anomaly region.

Availability: On two tapes (NSSDC ID **#PT-12A**, **#PX-21A**)

References:

D. Brouwer, Solution of the Problem of Artificial Satellite Theory Without Drag, *Astronom. J.* 64, 1959.

R. H. Lyddane, Small Eccentricities or Inclinations in the Brouwer Theory of Artificial Satellites, *Astronom. J.* 68, 1963.

A. B. Lucero, TRECO—An Orbital Integration Computer Program for Trapped Radiation, National Space Science Data Center, *Data User's Note NSSDC 68-02*, Greenbelt, Maryland, 1968.

M. J. Teague, J. Stein, and J. I. Vette, *The Use of the Inner Zone Electron Model AE-5 and Associated Computer Programs (ORP)*, NSSDC 72-11, Greenbelt, Maryland, 1972. (B14752)

M. J. Teague and J. I. Vette, *A Model of the Trapped Electron Population for Solar Minimum (ORB, ORP)*, NSSDC 74-03, Greenbelt, Maryland, 1974. (B19648)

SOFIP 1979

E. G. Stassinopoulos
(See address on page 4-29.)

Parameter: Integrated particle flux for geocentric satellites

Brief Description: The Short Orbital Flux Integration Program (SOFIP) is a computer code that has been developed to evaluate the space radiation environment encountered by geocentric satellites. It produces for a given input trajectory a composite integral orbit spectrum of either protons or electrons. Additional features include calculation of exposure index, peaks per orbit, percent time in electron trapping zones differential spectrum, and solar proton fluences (using SOLPRO). SOFIP is a structured, modularized code, which can perform all the functions of larger and more complex programs, if the correct modules are used. Care should be taken to use the correct epoch (1965 for solar minimum and 1970 for maximum) for the geomagnetic field in the calculation of magnetic field strength *B* and *L*-value. B/B_0 and *L* are needed to determine trapped particle fluxes with the help of the electron (AE) and proton (AP) models. Otherwise, erroneous fluxes may result at low altitudes.

Availability: On tape (NSSDC ID #**PT-15A**)

References:

E. G. Stassinopoulos, J. J. Hebert, E. L. Butler, and J. L. Barth, *SOFIP: A Short Orbital Flux Integration Program*, NSSDC 79-01, Greenbelt, Maryland, 1979.

SHIELDOSE 1980

S. Seltzer
Center for Radiation Research
National Bureau of Standards
Washington, D.C. 20234

Parameter: Absorbed dose in aluminum

Brief Description: SHIELDOSE is a computer code for space-shielding radiation dose calculations. It determines the absorbed dose as a function of depth in aluminum shielding material of spacecraft, given the electron and proton fluences encountered in orbit. The code makes use of precalculated, mono-energetic depth-dose data for an isotropic, broad-beam fluence of radiation incident on uniform aluminum plane media. These precalculated values are the result of detailed electron and electron-bremsstrahlung Monte Carlo calculations. The present version of SHIELDOSE calculates, for arbitrary proton and electron incident spectra, the dose absorbed in small volumes of the detector materials *Al*, H_2O (tissue-equivalent detector), *Si*, and SiO_2, in the following aluminum shield geometries: (1) in a semi-infinite plane medium, as a function of depth; (2) at the transmission surface of a plane slab, as a function of slab thickness; and (3) at the center of a solid sphere, as a function of sphere radius.

Availability: FORTRAN program on tape, SPAN (NSSDC ID #**PT-16A**)

References:

S. M. Seltzer, SHIELDOSE: A Computer Code for Space-Shielding Radiation Dose Calculations, National Bureau of Standards, *NBS Technical Note 1116*, U.S. Government Printing Office, Washington, D.C., 1980.

S. M. Seltzer, Electron, Electron-Bremsstrahlung, and Proton Depth-Dose Data for Space-Shielding Applications, *IEEE Trans. Nuclear Sci.* NS-26, 4896, 1979.

Spacecraft Radiation Exposure Studies 1972-1987

E. G. Stassinopoulos
NASA/GSFC, Code 933
Greenbelt, Maryland 20771

Parameter: Radiation exposure predictions for spacecraft missions.

Brief Description: These reports list and plot the radiation exposure that was predicted for several satellite missions. The calculations consider the contribution of electrons and protons trapped in Earth's radiation belt, of cosmic ray particles, and of solar protons.

Availability: Microfiche (Please order by *B* number.)

Title	NSSDC ID	GSFC Report	B-Number	Microfiche Quantity
SKYLAB Radiation Study	–	–	B12490	–
AE-C Radiation Study	–	–	B12492	–
UK-4 Radiation Study	**MT-32A**	X-601-72-131	B12856	1
UK-5 Radiation Exposure	**MT-32B**	X-601-72-308	B17030	7
TIROS-N Radiation Levels	**MT-32C**	X-601-72-429	B14636	1
ERTS/NIMBUS Radiation Environment	**MT-32D**	X-601-73-122	B15666	2
OSO Missions Radiation Environment	**MT-32E**	X-601-73-168	B16342	4
Rad. Hazards to Synchronous Satellite	**MT-32F**	X-601-73-330	B18453	6
SATS Radiation Environment	**MT-32G**	X-601-73-384	B18452	10
ATS-F Radiation Environment	**MT-32H**	X-601-74-21	B18450	2
Project SOLRAD	**MT-32I**	X-601-74-81	B18659	2
ISEE Radiation Study	**MT-32J**	X-601-74-204	B19968	3
Project SOLWIND	**MT-32K**	X-601-75-070	B22714	2
LDEF Radiation Levels	**MT-32L**	X-601-75-170	B23791	2
AE-E Radiation Exposure	**MT-32M**	X-601-75-234	B24452	1

Title	Publication Date	GSFC Report	B-Number
IUE Radiation Environment	1/78	–	B29833
IRAS Radiation Study	12/78	–	B32196
NTS-2/-3 Study	12/79	–	B32195
GRO Radiation Study	12/81	–	B33341
CRRES Radiation Study	12/82	–	B35632
GOES Missions	1/84	–	B35608
ROSAT Radiation Study	3/84	–	B35609
EOS Radiation Study	6/84	–	B35763
Space Station	11/86	X-600-87-5 and -6	–

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SUN AND INTERPLANETARY SPACE

Our Sun radiates nearly all its energy in the ultraviolet (UV) through the infrared (IR) part of the spectrum. The solar photon flux is nearly constant at these wavelengths, providing Earth with the steady input of radiative energy that has permitted terrestrial life to evolve and to flourish. At higher wavelengths, however, in the EUV, X-ray, and gamma-ray part of the spectrum, the solar radiative output is highly variable. Only two **reference spectra** are listed in this catalog: (1) the high resolution IR spectra obtained with the Shuttle/Spacelab ATMOS experiment, and (2) the EUV spectrum deduced from AE spectrometer data. The latter is important for aeronomic model calculations.

The solar particle output also exhibits strong variations. It consists of low energy particles forming the solar wind and high energy electrons, protons, and heavier ions, which are the result of solar flares. Solar flares occur when the energy stored in the twisted magnetic loops that extend out into space from the Sun's surface is released suddenly, accelerating electrons and ions to high energies.

The cyclic behavior of the variable part of the solar spectrum is closely related to the behavior of the **solar indices *R*** (sunspot number) and ***F10.7*** (10.7 cm radio flux). The availability of these solar indices and of **solar wind parameters** is described in the section on solar-terrestrial indices (see pages 7-8 to 7-12).

Predictability of the fluences of **solar flare protons** and **cosmic rays** (atomic nuclei, mostly protons, of high energy and galactic origin) is an essential requirement for the assessment of radiation hazards to humans and materials in space. The widely used sophisticated CREME computer code considers cosmic rays and solar protons (as well as trapped particles), whereas the SOLPRO and JPL subroutines determine interplanetary proton fluences only. The disturbing effect of high energy radiation and particles on orbiting spacecraft is documented in the Spacecraft Anomaly Data Base that is being maintained at the National Geophysical Data Center (NGDC) in Boulder, Colorado.

IR Spectrum of Sun and Earth Atmosphere

1989

C. B. Farmer, R. H. Norton
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

Parameter: Spectral intensity from 650 to 4800 cm^{-1}

Brief Description: This data set is a high resolution atlas of the infrared spectrum of the Sun and the Earth atmosphere. The spectra are compiled from solar occultation observations made by the Atmospheric Trace Molecule Spectroscopy (ATMOS) experiment on Spacelab 3 during a Shuttle mission in 1985. The atlas is believed to be the first record of continuous high resolution (0.01 cm^{-1}) infrared spectrum of the Sun and the Earth atmosphere from space. It is presented in two volumes: The first contains the solar spectra covering the entire frequency range of the instrument (650 to 4800 cm^{-1}), and the second covers the atmospheric spectra for tangent altitudes between 23 km and 80 km, at approximately one-scale-height intervals (8 km), for the frequency range from 650 to 3380 cm^{-1}.

Availability: As hard copy NASA report. A CD-ROM containing the whole atlas is being prepared at the Jet Propulsion Laboratory.

References:

C. B. Farmer and R. H. Norton, A High Resolution Atlas of the Infrared Spectrum of the Sun and the Earth Atmosphere from Space, Volume I. The Sun (650 to 4800 cm^{-1}), Volume II. Stratosphere and Mesosphere (650 to 3350 cm^{-1}), National Aeronautics and Space Administration, *Reference Publication 1224*, Washington, D.C., 1989.

Revised SERF2 Solar EUV Flux Model

1990

W. K. Tobiska
Space Science Laboratory
University of California
Berkeley, California 94720
SPAN: UCBSP::KENT

Parameter: Solar photon fluxes between 1.8 and 105 nm

Brief Description: This is an extended and revised solar extreme ultraviolet irradiance model for aeronomical use during the 1990s. The extensions significantly increase the application of the SERF2 solar EUV model beyond the October 1981-April 1989 time frame. The model can now be used from 1947 to the present for coronal EUV full-disk irradiances and from 1976 to the present for chromospheric EUV full-disk irradiances. Substantial revisions were made to SERF2 that significantly improve the ability of the model to reproduce observed 27-day and solar cycle EUV temporal variations. A multiple linear regression method is used to obtain coefficients for modeled EUV photon flux. This method allows for the inclusion of new rocket and satellite data sets into the model as they become available. The solar H Lyman-alpha, lya, and He I 10,830 Å equivilant width measurements are used as the independent model parameters for the chromospheric irradiances while the 10.7 cm radio emission daily and 81-day running mean values are the independent parameters for the coronal and transition region irradiances. The results of the model give full-disk photon fluxes at 1 AU for 39 EUV wavelength groups and discrete lines between 1.8 and 105.0 nm for a given date. OSO, AEROS, AE satellite data sets and five rocket data sets are used in the model development.

Availability: From NSSDC shortly. Inquiries should be addressed to Request Coordination, GSFC, NSSDC, Code 933, Greenbelt, Maryland 20771, SPAN: NCF::REQUEST.

References:

J. L. Lean, Solar Ultraviolet Irradiance Variations: A Review, *J. Geophys. Res.* 92, 839, 1978.

W. K. Tobiska and C. A. Barth, A Solar EUV Flux Model, *J. Geophys. Res.* 95, 8243, 1990.

W. K. Tobiska, Revised Solar Extreme Ultraviolet Flux Model, submitted to *J. Atmos. Terr. Phys.* July 1990.

EUV Reference Spectrum 74113 — 1978

J. E. Hinteregger
Air Force Geophysics Laboratory
Hanscom Air Force Base
Bedford, Massachusetts 01731

Parameter: Solar photon fluxes from 15 to 2000 Å

Brief Description: This data set consists of the two solar Extreme Ultraviolet (EUV) reference spectra R74113 and F74113 compiled by H. E. Hinteregger based on rocket measurements conducted on April 23, 1974, and simultaneously obtained EUV fluxes by his AE-E spectrometer. The rocket measurements were used to establish absolute calibration factors for the AE-E instrument. The original proposed R74113 spectrum (Hinteregger, 1976) was revised to become F74113 (Heroux, Hinteregger, 1978), following refined evaluation of the rocket data and detailed analysis of the long record of AE-E measurements. F74113 is representative for solar minimum conditions and has been widely used in aeronomical studies. The solar sunspot minimum was recorded in July 1976. By that time, however, the photon fluxes had already increased again by about 30%, i.e., the solar cycle variations of sunspot numbers and photon fluxes were out of phase. It has also been found that the variation of photon fluxes over one solar cycle is strongly wavelength dependent. Nevertheless, in most aeronomical computations the solar cycle variation of EUV photon fluxes is modeled by using the F74113 reference spectrum together with one of the solar indices (e.g., Hinteregger et al., 1981).

Availability: On one tape (NSSDC ID #**RS-12B**)

References:

H. E. Hinteregger, Measurement of Solar Flux Intensities Below About 2000 Å, *J. Atmos. Terr. Phys.* 38, 701, 1976.

L. Heroux and H. E. Hinteregger, Aeronomical Reference Spectrum for Solar UV Below 2000 Å, *J. Geophys. Res.* 83, 5305, 1978.

H. E. Hinteregger, K. Fukui, and B. R. Gilson, Observational, Reference and Model Data on Solar EUV, from Measurements on AE-E, *Geophys. Res. Lett.* 8, 1147, 1981.

G. Schmidtke, Modeling of the Solar Extreme Ultraviolet Irradiance for Aeronomic Applications, *Encyclopedia of Physics XLIX/7*, K. Rawer (ed.), Springer-Verlag, Berlin, 1984.

C. A. Barth, W. K. Tobiska, G. J. Rottman, and O. R. White, Comparison of 10.7 cm Radio Flux with SME Solar Lyman Alpha Flux, *Geophys. Res. Lett.* 17, 571, 1990.

SOLPRO Model 1975

E. G. Stassinopoulos
NASA/GSFC, Code 933
Greenbelt, Maryland 20771

Parameter: Solar proton fluences (10 MeV to 100 MeV)

Brief Description: SOLPRO is the computer version of the interplanetary proton fluence model developed by King (1974) and Stassinopoulos and King (1974). The model is based on the most continuous set of satellite data available at the time covering the period of enhanced solar activity during solar cycle 20 (1964-1972). Because of its size, the August 1972 event produced a fluence more than a factor of 10 larger than any other event in cycle 20. For that reason, King (1974) treats this event separately and calls it an anomalously large (AL) event. The FORTRAN subroutine SOLPRO calculates the interplanetary solar proton fluences (at 1 A.U. [Astronomical Unit] = Earth-Sun distance) as a function of mission duration (in months), energy threshold (in MeV), and confidence level (in percent). For a given combination of input parameters, the code determines whether an anomalously large (AL) event needs to be considered and, if so, how many. For missions whose trajectories involve significant time away from a heliocentric distance of 1 A.U., a helioradial dependence of event fluences must be considered (King, 1974). Similarly, for missions whose trajectories involve partial magnetospheric shielding, the fractional exposure factor has to be determined (Stassinopoulos and King, 1974). The model strongly depends on the fluence of the 1972 AL event. This has led to over-predictions for cycle 21. Cycle 21 did not show a major event.

Availability: On tape or SPAN (NSSDC ID #**MZ-14A**)

References:

J. H. King, Solar Proton Fluences for 1977-1983 Space Missions, *J. Spacecraft Rockets* 11, 401, 1974. (B18663)

E. G. Stassinopoulos and J. H. King, Empirical Solar Proton Model for Orbiting Spacecraft Applications, *IEEE Trans. Aerospace Electronic Systems* 10, 4, 1974. (B17234)

J. H. King and E. G. Stassinopoulos, Energetic Solar Protons vs. Terrestrially Trapped Proton Fluxes for the Active Years 1977-1983, *J. Spacecraft Rockets* 12, 122, 1975. (B20337)

E. G. Stassinopoulos, *SOLPRO: A Computer Code to Calculate Probabilistic Energetic Solar Proton Fluences*, NSSDC 75-11, Greenbelt, Maryland, 1975. (B23274)

JPL Proton Model 1989

J. Feynman
Jet Propulsion Laboratory
Pasadena, California 91101

Parameter: Interplanetary proton fluences (E > 10 MeV and E > 30 MeV)

Brief Description: This model describes the interplanetary fluences of protons with energies greater than 10 MeV and also of protons with energies greater than 30 MeV at a distance of one Astronomical Unit (A.U. = Earth-Sun distance). It is based on riometer, rocket, and balloon measurements from the Earth's surface and from above the atmosphere between 1956 and 1963, and on spacecraft measurements in the vicinity of Earth between 1963 and 1985. Altogether, close to 200 events are considered. The distribution of event fluences is represented by a log normal distribution. Because of the larger data base a distinction between "ordinary" and "anomalously large" (AL) events, as in the SOLPRO model, is not necessary; the August 1972 AL does not stand out from the rest of the data base. Fluences during the seven active years of a solar cycle exceed fluences during the four quiet years by at least two orders of magnitude. The active period starts about two years before the sunspot maximum and lasts for about seven years. To obtain proton fluences from this model, one has to specify (1) the mission length at a constant heliocentric distance of 1 A.U. during the active years, and (2) the required confidence level. A confidence level of 95% means that only 5% of missions identical to the one being considered will have fluences larger than those predicted by the model. For distance r less than 1 A.U. an r^{-3} fluence dependence is recommended and for r greater than 1 A.U., an r^{-2} dependence. The proton fluences for energies greater than 10 MeV are about twice those calculated with earlier models. At energies greater than 30 MeV, the old and new models agree. In general, the JPL model can be considered the most reliable at this time because of the large data base used.

Availability: FORTRAN program is available from the authors.

References:

J. Feynman, T. P. Armstrong, L. Dao-Gibner, and S. Silverman, New Interplanetary Proton Fluence Model, *J. Spacecraft and Rockets*, accepted September 1988.

J. Feynman, T. P. Armstrong, L. Dao-Gibner, and S. Silverman, Solar Proton Events During Solar Cycles 19, 20, and 21, *Solar Phys.*, accepted November 1989.

CREME Programs

1986

J. H. Adams, Jr.
Naval Research Laboratory, Code 4154.2
Washington, D.C. 20375
SPAN: 11335::ADAMS

Parameter: Differential and integral energy and LET spectra of cosmic rays; single event upset (SEU) rates

Brief Description: The Cosmic Ray Effects on Microelectronics (CREME) software package allows a spacecraft designer or operator to estimate error rates arising from cosmic ray bombardment of satellite microelectronics. Program functions include calculation of (1) differential and integral cosmic ray flux (for any element) vs. particle energy or vs. linear energy transfer (LET), (2) geomagnetic shielding for a given orbit using the tabulation of geomagnetic cutoff values by Shea and Smart (1975) as described by Adams et al. (1983), (3) ordinary and worst-case solar flare proton fluxes, and (4) single event upset rates for microelectronics in the orbiting satellite.

Availability: On tape from the National Geophysical Data Center, E/GC2, 325 Broadway, Boulder, Colorado 80303, (303) 497-6346 ($90)

References:

M. E. Shea and D. F. Smart, Tables of Asymptotic Directions and Vertical Cutoff Rigidities for a Five Degree by Fifteen Degree World Grid as Calculated Using the International Geomagnetic Reference Field for Epoch 1975.0, Air Force Geophysics Laboratory, *Report AFCRL-TR-75-0185*, Hanscom AFB, Massachusetts, 1975. (AD-A012509)

J. H. Adams, R. Silberberg, and C. H. Tsao, Cosmic Ray Effects on Microelectronics, Part I: The Near-Earth Particle Environment, Navy Research Laboratory, *NRL Memorandum Report 4506*, Washington, D.C., 1981. (AD-A103897)

J. H. Adams, J. R. Letaw, and D. F. Smart, Cosmic Ray Effects on Microelectronics, Part II: The Geomagnetic Cutoff Effects, *NRL Memorandum Report 5099*, Washington, D.C., 1983. (AD-A128601)

C. H. Tsao, R. Silberberg, J. H. Adams, and J. R. Letaw, Cosmic Ray Effects on Microelectronics, Part III: Propagation of Cosmic Rays in the Atmosphere, *NRL Memorandum Report 5402*, Washington, D.C., 1984. (AD-A145026)

J. H. Adams, Cosmic Ray Effects on Microelectronics, Part IV, *NRL Memorandum Report 5901*, Washington, D.C., 1986.

Spacecraft Anomaly Data Base

1988

D. C. Wilkinson
NOAA E/GC2
325 Broadway
Boulder, Colorado 80303
(303) 497-6137

Parameter: Spacecraft operational irregularities archived by time and location

Brief Description: NOAA's National Geophysical Data Center (NGDC) in Boulder, Colorado, maintains a data base of spacecraft anomalies, ranging from minor operational problems to permanent spacecraft failures. The data base includes anomalies primarily from geostationary spacecraft as well as near-Earth and interplanetary space failures. It currently contains 2779 events from 1971 to the present. Events were contributed from seven countries: Australia, Canada, Germany, India, Japan, the U.K., and the U.S.A. Data suppliers usually provide the anomaly type and diagnosis. The Spacecraft Anomaly Manager (SAM) software allows the user to select specific anomalies and to depict them in local time and seasonal histograms. SAM was designed as a tool to investigate the relationship between anomaly frequency and environmental factors.

Availability: On two diskettes for use on PCs (Data Base and SAM, $60) from NGDC

References:

D. C. Wilkinson, Trends in Environmentally Induced Spacecraft Anomalies, in: NASA/SDIO Space Environmental Effects on Materials Workshop, 123-131, *NASA Conference Publication 3035, Part 1*, Washington, D.C., 1989.

PLANETS

Only a few empirical models have been established for the ionospheres, atmospheres, and magnetospheres of the planets in the solar system because of the limited data base. This report lists software for models of the Venus ionosphere and thermosphere based on the Pioneer Venus measurements.

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PV Thermospheric Model 1983

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Greenbelt, Maryland 20771
SPAN: DE614::HEDIN, PACF::HEDIN

Parameter: CO_2, *O*, *CO*, N_2, *He*, and *N* densities and exospheric temperature

Brief Description: The model describes the neutral densities and temperature in the Venus thermosphere in the altitude range 140 km to 250 km. It is based on Pioneer Venus Orbiter (PVO) data from the Orbiter Neutral Mass Spectrometer (ONMS) and on some density data from the entry probe. The model formulation relies on modified Bates temperature profiles and the related diffusive equilibrium density profiles. There are less than 15 coefficients per individual density model.

Availability: On tape, SPAN (NSSDC ID #**MN-62A**)

References:

A. E. Hedin, H. B. Niemann, W. T. Kasprzak, and A. Seiff, Global Empirical Model of the Venus Thermosphere, *J. Geophys. Res.* 88, 73, 1983.

PV Ionospheric Model 1984

R. F. Theis
NASA/GSFC, Code 614
Greenbelt, Maryland 20771
PACF::THEIS

Parameter: Electron density and temperature

Brief Description: The model is based on Pioneer Venus Orbiter (PVO) data from the orbiter electron temperature probe (OETP) from the first seven Venus years (12/78 - 12/82). About 35,000 data points are used to describe the electron density and temperature in the Venus ionosphere in the altitude range from 150 km up to the ionopause (about 500 km in daytime and about 3000 km at nighttime). Whereas an earlier model (Theis et al., 1980) used spherical harmonics to describe the solar zenith variation, this model uses error functions. Thirty-two coefficients are needed for the electron temperature model and 26 coefficients for the electron density.

Availability: On tape, SPAN (NSSDC ID #**MI-94A**)

References:

R. F. Theis, L. H. Brace, and H. G. Mayr, Empirical Models of the Electron Temperature of the Venus Ionosphere, *J. Geophys. Res.* 85, 7787, 1980.

R. F. Theis, L. H. Brace, R. C. Elphic, and H. G. Mayr, New Empirical Models of the Electron Temperature and Density in the Venus Ionosphere with Applications to Transterminator Flow, *J. Geophys. Res.* 89, 1477, 1984.

Venus International Reference Atmosphere 1985

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Moscow 117810
U.S.S.R.

G. M. Keating
NASA/Langley Research Center
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Parameter: Venus atmospheric and ionospheric parameters

Brief Description: This is a document summarizing the physical properties of the atmosphere and ionosphere of Venus as observed by the Venera and Pioneer space probes. The Venus International Reference Atmosphere (VIRA) is the result of international collaboration and data exchange guided by a specially formed COSPAR task group. The VIRA document is divided into seven chapters, covering the structure below 100 km (A. Seiff et al.), circulation (V. V. Kerzhanovich, S. S. Limayl), particulate matter (B. Ragent et al.), structure and composition of the upper atmosphere (G. M. Keating et al.), composition below the homopause (V. von Zahn, V. I. Moroz), solar and thermal radiation balance (V. I. Moroz et al.), and the ionosphere and solar wind interaction (S. J. Bauer et al.). Several tables of reference values for densities and temperature can be found in all the chapters.

References:

A. J. Kliore, V. I. Moroz, and G. M. Keating (eds.), The Venus International Reference Atmosphere, *Adv. Space Res.* 5, #11, 1-305, 1985.

SOLAR-TERRESTRIAL INDICES

Most solar-terrestrial models need solar and geomagnetic indices to specify the solar and magnetic disturbance level. These indices are usually parameters that can be monitored continuously with ground-based equipment or that can be derived from continuously monitored parameters. Long data records from the past are a necessity for reliable forecasts of these indices in the future. In the section below, the most important solar-terrestrial parameters are explained. For a detailed description of geomagnetic indices, we recommend the book published in 1980 under the title of *Derivation, Meaning, and Use of Geomagnetic Indices* by P. N. Mayaud (American Geophysical Union, Geophysical Monograph 22). Solar indices and their applicability to ionospheric/atmospheric studies are discussed by J. Lean in *Advances in Space Research*, Volume 8, Number 5, pages 263-292, 1988.

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Sunspot Number

The sunspot number index R is a measure of the area of solar surface covered by spots. As the number of spots increases and their magnetic complexity grows, they become likely sources of large eruptive energy releases known as solar flares. The sunspot number index is also often called Wolf number in reference to the Swiss astronomer J. R. Wolf who introduced this index in 1848. Since for many years solar sunspot numbers were derived at the Zurich Observatory, this index is known as Zurich Sunspot Number *Rz*. Since 1981 an International Sunspot Number *Ri* is derived by A. Koeckelenbergh at the World Data Center C for Sunspots in Brussels, Belgium. Both *Rz* and *Ri* are calculated as a weighted mean of spots and spot groups reported by a network of solar observatories. Sunspot numbers have also been prepared by the American Association of Variable Star Observers (*Ra*). Besides daily, monthly, and yearly averages, a 12-month running mean value, R_{12}, is calculated. Yearly sunspot numbers are available since the telescope was invented in 1610. A long period of very low sunspot numbers in the last half of the seventeenth century is known as Maunder minimum. In 1842, H. Schwalbe noticed that the number of spots varies with a period of about 11 years. Analyzing the long record of observations, it has been found that the cycle period varies from ten to 12 years with a mean of 11 years. The average time from cycle minimum to maximum is 4.3 years and from maximum to minimum 6.6 years. Cycles (from minimum to maximum) are numbered chronologically. The present cycle is number 22 and had its minimum in September 1986. Solar magnetic polarity reverses during sunspot maximum, so the solar magnetic cycle has a 22-year periodicity.

Ottawa 10.7 cm (2800 MHz) Solar Radio Flux

The sun emits radio energy with slowly varying intensity. This radio flux, which originates from atmospheric layers high in the sun's chromosphere and low in its corona, changes gradually from day to day in response to the number of spot groups on the disk. Solar flux from the entire solar disk at a frequency of 2800 MHz has been recorded routinely by radio telescope near Ottawa since February 1947. The observed values are adjusted for the changing Sun-Earth distance (adjusted values) and for uncertainties in antenna gain (absolute values). Fluxes are given in units of 10^{-22} J s^{-1} m^{-2} Hz^{-1}. Often used names for this index are *F10.7* and *Covington* index. Empirical formulas have been established for the relationship between F10.7 and solar sunspot number (see below).

I_{F2}, *IG* Ionospheric Indices

It has long been noted that solar sunspot number (*R*) and solar radio flux (*F10.7*) are not the perfect indices for describing the variation of ionospheric parameters with changing solar EUV irradiance. The relationship between *R* and *F2*-peak plasma frequency *foF2* does not remain constant from cycle to cycle and does not remain linear (a saturation effect is seen at high levels of solar activity). To overcome these problems, C. M. Minnis devised the ionospheric index I_{F2} in 1955 based on *foF2* values measured at three representative ionosonde stations. For each station the linear regression coefficients α, β are determined for the correlation between the monthly median noon *foF2* and the three-month-running mean value of the sunspot number R_3. A corrected R' is then obtained by substituting measured *foF2* values in the linear relation: $R_3' = \alpha \bullet foF2 + \beta$. I_{F2} is defined as the mean value of R_3' for the three stations. Since 1960 the calculation scheme has been extended to average over 13 worldwide stations. In 1983 Liu, Smith, and King (*Telecomm. J.* 50, 408, 1983) proposed a slightly different scheme to obtain a "global" ionospheric parameter *IG*, based on the CCIR *foF2* model. I_{F2} and *IG* values are available for each month since 1938.

Correlation Among Monthly Solar Activity Indices

Strong correlations have been observed among the different solar indices. They also correlate strongly with the solar irradiance at different wavelengths; the correlation parameters, however, vary with wavelength.

The following are the correlations recommended for use by the International Radio Consultative Committee (CCIR):

$$F10.7 = R_{12} + 46 + 23 \bullet e^{-0.05 R_{12}}$$

$$F10.7_{12} = 63.7 + 0.728 R_{12} + 8.9 \bullet 10^{-4} (R_{12})^2$$

$$R_{12} = 11.44 + 0.478 I_{F2} + 0.00278 \bullet (I_{F2})^2$$

$$I_{F2} = (2.05 + 0.001 R_{12}) R_{12}^{0.946-0.00047 R_{12}} - 20$$

Kp Index

Geomagnetic disturbances (storms) can be monitored by ground-based magnetic observatories recording the horizontal magnetic field components. The global or planetary *Kp* index is obtained as the mean value of the disturbance levels observed at 12 selected, subauroral stations. Local disturbance levels are determined by measuring the range (difference between the highest and lowest values) during three-hourly time intervals for the most disturbed magnetic field component. First, however, the quiet-day variation pattern has to be removed from the magnetogram, a somewhat subjective procedure. The range is then converted into a local *K* index taking the values 0 to 9 according to a pseudo-logarithmic scale, which is station specific; this is done in an attempt to normalize the frequency of occurrence of the different sizes of disturbances. The three-hourly *Kp* index (average of local *K* values from 12 stations) is expressed in a scale of thirds (28 values):

$$0_0, 0+, 1-, 1_0, 1+, 2-, 2_0, 2+, \ldots, 8_0, 8+, 9-, 9_0$$

Kp was introduced as magnetic index by J. Bartels in 1938 and has been derived since then at the Geophysical Institute of Göttingen University, Federal Republic of Germany. A daily index ΣKp is obtained by summing the eight three-hourly values for that day. *Kp* and its related indices (*ap, Ap, Cp*) have been widely used in ionospheric and atmospheric studies and are generally recognized as indices measuring the effect of energetic charged particles arriving in Earth's upper atmosphere after periods of intense solar activity. *Km* is an index derived similarly as *Kp* except the number and selection of stations is different. *Km* is evaluated at the Institute de Physique du Globe in Paris, France.

ap, Ap, Cp, and *C9* Indices

All these indices are directly related to *Kp*. The *Kp* index has a semi-logarithmic relationship with the range *r*. In order to obtain a linear scale from *Kp*, Bartels gave the following table to derive a three-hour *ap* index.

Kp	0_0	0+	1–	1_0	1+	2–	2_0	2+	3–	3_0	3+	4–	4_0	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp	5–	5_0	5+	6–	6_0	6+	7–	7_0	7+	8–	8_0	8+	9–	9_0
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

This table is made in such a way that at a station at about dipole latitude 50°, *ap* may be regarded as the range of the most disturbed of the three field components, expressed in the unit of 2 γ. A daily index *Ap* is obtained by averaging the eight values of *ap* for each day. *Am* and *am* indices are derived in a similar fashion from *Km*. The *Cp* index, the daily planetary character figure, is defined on the basis of *Ap* according to the following table.

Cp	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Ap	2	4	5	6	8	9	11	12	14	16	19
Cp	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	
Ap	22	26	31	37	44	52	63	80	110	160	

Another index devised to express geomagnetic activity on the basis of the *Cp* index is the *C9* index which has the range between 0 and 9. The conversion table from the *Cp* index to the *C9* index is as follows.

Cp	0.0-0.1	0.2-0.3	0.4-0.5	0.6-0.7	0.8-0.9
C9	0	1	2	3	4
Cp	1.0-1.1	1.2-1.4	1.5-1.8	1.9	2.0-2.5
C9	5	6	7	8	9

Dst Index

The *Dst* index monitors the variations of the globally symmetrical ring current, which encircles the Earth close to the magnetic equator in the Van Allen (or radiation) belt of the magnetosphere. During large magnetic storms the signature of the ring current can be seen in ground magnetic field recordings worldwide as so-called main phase depression. The ring current energization which results in typical depression of 100 nT is related to magnetic reconnection processes at the neutral sheet. Several steps are necessary to isolate the equivalent ring current disturbance from H-component magnetic recordings. After this is accomplished for a worldwide array of low-latitude observatories, the residual variations are transformed to their equatorial equivalent, and harmonic analysis is applied to obtain the term used as *Dst* index. Hourly *Dst* indices since 1957 have been derived by Sugiura and his co-workers at the NASA Goddard Space Flight Center and the World Data Center in Kyoto, Japan. *Dst* responds better than *AE* to changes of solar wind parameters during intense storms.

AE, AU, AL, AO Indices

The *AE* and related indices were devised by T. N. Davis and M. Sugiura in 1966. These indices describe the disturbance level recorded by auroral zone magnetometers. Horizontal magnetic component recordings from a set of globe-encircling stations are plotted to the same time and amplitude scales relative to their quiet-time levels and then graphically superposed. The upper and lower envelopes of this superposition define the *AU* (amplitude upper) and the *AL* (amplitude lower) indices, respectively. The difference between the two envelopes determines the *AE* (Auroral Electrojet) index, i.e., $AE = AU - AL$. *AO* is defined as the average value of *AU* and *AL*. Hourly *AE* indices since 1957 were derived at the Geophysical Institute of the University of Alaska and the NASA Goddard Space Flight Center from hand-scaled values. For years 1966 through 1974, *AE* and related indices were derived at the National Geophysical Data Center (NGDC) in Boulder, Colorado, from 2.5-minute digitized values scaled by semi-automatic machines from analog magnetograms. Beginning in 1975, NGDC produced one-minute indices including data from digital magnetometers.

Summary List of Geomagnetic Indices

aa	3-hour range index, derived from two antipodal stations
AE, AU, AL	2.5-minute or hourly auroral electrojet indices
am, an, as	3-hour range (mondial, northern, southern) indices
ap	3-hour range planetary index derived from *Kp*
C, Ci, C9	Daily local (*C*) or international (*Ci*) magnetic character; *C9* was first derived from *Ci*, then from *Cp*
Cp	Daily magnetic character derived from *Kp*
Dst	Hourly index mainly related to the ring current
K	3-hour local quasi-logarithmic index
Km	3-hour mean index derived from an average of *K* indices (not to be confused with the *Km* of the next item)
Km, Kn, Ks	3-hour quasi-logarithmic (mondial, northern, southern) indices derived from *am, an, as*
Kp, Ks	3-hour quasi-logarithmic planetary index and the intermediate standardized indices from which *Kp* is derived (not to be confused with the *Ks* of the preceding item)
Kw, Kr	3-hour quasi-logarithmic worldwide index and the intermediate from which *Kw* is derived
Q	Quarter hourly index
R	1-hour range index
R_X, R_Y, R_Z	Daily ranges in the field components
σn, σs	3-hour indices associated with *an* and *as*
U, u	Daily and monthly indices mainly related to the ring current
W	Monthly wave radiation index

Solar-Terrestrial Indices on Diskette and Tape

Information Services Division
Mail Code E/GC2
National Geophysical Data Center
325 Broadway
Boulder, Colorado 80303
(303) 497-6346

- *Zurich and International Sunspot Numbers:* Daily means from 1818 to present, monthly and smoothed monthly means from 1749 to present, and yearly means from 1700 to present. Available on two diskettes, in hard copy (*Report UAG-95*, 112 pages), and as four publication quality plots.
- *Ottawa 10.7 cm (2800 MHz) Solar Flux:* Observed, adjusted, and absolute daily values, monthly means, and yearly means from February 1947 to present. Available on two diskettes and in hard copy (46 page booklet).
- *Solar Irradiance:* Daily measurements by the Nimbus and SMM satellites of the total energy emitted by the sun from November 1978 to present. Available on one diskette and in hard copy (19 page booklet).
- *Solar EUV Flux (168-1216Å):* Daily full-disk spectral irradiances taken by the Atmospheric Explorer-E satellite from July 1977 to December 1980. Available on two diskettes.
- *Solar X-Ray Fluxes (0.5-4Å, 1-8Å):* Continuous three-second whole-sun fluxes obtained at geostationary altitude by the SMS/GOES satellites from July 1974 to present. Available on magnetic tape (one tape per month).
- *Geomagnetic Indices: Kp, ΣKp, ap, Ap, Cp, C9, sunspot number, 10.7-cm solar flux* from January 1932 to present. Available on magnetic tape and on six diskettes (Disk 1: 1932-1942, Disk 2: 1943-1953, Disk 3: 1954-1964, Disk 4: 1965-1975, Disk 5: 1976-1986, Disk 6: 1987-present).
- Equatorial *Dst* from 1957 to 1984 on magnetic tape.
- Worldwide three-hourly *aa* indices from 1869-1987 on magnetic tape.
- Daily *aa* indices and IMF directions from 1974 to present on diskette.
- IMF sector boundary crossings from 1947 to 1978 on diskette.
- Hourly *AE* and components from 1957 to 1984 on magnetic tape.
- 2.5-minute *AE* and components from 1966 to 1974 on magnetic tape (two).
- One-minute *AE* and components from 1975 and from 1978 to 1984 on magnetic tape (four).
- Continuous three-second geomagnetic field components, proton fluxes (0.8-500 MeV), electron fluxes above 2 MeV, and alpha particles (4-392 MeV) observed by the SMS/GOES satellite at geostationary altitudes from July 1974 to present. Available on magnetic tape (one month per tape.)

All diskettes are 5 ¼ inch, double-sided, double-density for use on IBM compatible XT or AT personal computers (PCs). Please contact the National Geophysical Data Center (NGDC) for prices and a full list of available data sets.

Solar-Terrestrial Indices on CD-ROM

Information Services Division
National Geophysical Data Center
Mail Code E/GC2
325 Broadway
Boulder, Colorado 80303
(303) 497-6346

This CD-ROM, entitled *Selected Geomagnetic and Other Solar-Terrestrial Physics Data of NOAA and NASA*, includes:

- Hourly, daily, monthly, and annual mean geomagnetic field elements from a large number of observatories.
- One-minute values of magnetic field components recorded at the 11 U.S. observatories during 1984.
- Hourly *AE* indices beginning in July 1957 at the start of the International Geophysical Year (IGY) and continuing through December 1983. Hourly *AU, AL*, and *AO* from 1966 through 1983.
- Hourly *Dst* indices for years 1957 through 1984.
- Three-hourly *Kp* indices and related *ap* and *Ap* indices from 1932 through early 1987.
- Solar flare list from July 1955 through February 1987 giving the starting time, X-ray class, location on run, and several more flare characteristics.
- Epochs of sunspot maximum and minimum from 1610 through 1985.
- Sunspot numbers: Daily since 1848, monthly since 1749, yearly since 1749, weighted 13-month running mean since 1749.
- Hourly solar wind and Interplanetary Magnetic Field (IMF) parameters from OMNI tape (see next entry).
- Catalog of data sets from ionosondes deposited with the World Data Centers.

This CD-ROM was created by the National Geophysical Data Center (NGDC) in 1987. NGDC also provides accession and plotting software on diskette. Please contact NGDC for prices.

Interplanetary Plasma and Field Parameters (OMNI Tape)

J. H. King
NASA/GSFC, Code 933
Greenbelt, Maryland 20771
(301) 286-7355
SPAN: NCF::KING

Parameter: Hourly solar wind and IMF parameters since 1963, also *Kp*, *C9*, *Rz*, and *Dst*

Brief Description: This data set consists of hourly averaged interplanetary plasma and magnetic field parameters from 1963 to the present. The compilation is based on IMP-A, -C, -D, -E, -F, -G, -H, -J, Vela 2-6, OGO 5, HEOS, ISEE 1 and 3, and Prognoz 10 plasma and field measurements. Several reports discuss the data sources, their mutual consistency, the plasma normalization, and the limits of accuracy. Computer generated listings and graphs show solar wind parameters (bulk speed, density, temperature) and Interplanetary Magnetic Field (IMF) parameters (magnitude, vector components, and angles). These parameters are part of the OMNI tape that is maintained and periodically updated at NSSDC.

Availability: On tape (NSSDC ID #**SM-41B**). The 1973-1989 portion of the OMNI tape's content is accessible on line in NSSDC's NODIS account. The 1964-1985 portion is included in the National Geophysical Data Center's (NGDC) CD-ROM of solar terrestrial indices.

References:

J. H. King, *Interplanetary Medium Data Book, 1963-1975*, NSSDC 77-04, Greenbelt, Maryland, 1977. (discussion, graphs)

J. H. King, *Interplanetary Medium Data Book, 1963-1975, Appendix*, NSSDC 77-04a, 1977. (listing)

J. H. King, *Interplanetary Medium Data Book, Supplement 1, 1975-1978*, NSSDC 79-08, 1979. (listing, graphs)

D. A. Couzens and J. H. King, *Interplanetary Medium Data Book, Supplement 3, 1977-1985*, NSSDC 86-04, 1986. (discussion, graphs)

D. A. Couzens and J. H. King, *Interplanetary Medium Data Book, Supplement 3a*, NSSDC 86-04a, 1986. (listing)

J. H. King, *Interplanetary Medium Data Book, Supplement 4, 1985-1989*, NSSDC 89-17, 1989. (listing, graphs)

Solar Terrestrial Indices in Journals and Reports

Preliminary Report and Forecast of Solar Geophysical Data

Published weekly by the joint NOAA-U.S. Air Force Space Environment Services Center (SESC), 325 Broadway, Boulder, Colorado 80303-3328.

- Daily Solar Indices: *F10.7*, *R*, proton and electron fluence
- Daily Geomagnetic Indices: *K*, *Kp*
- Forecast (30 Days): *F10.7*, *Ap*, largest *Kp*
- Alerts and Forecast: Solar flare, energetic particle events

SESC also provides telephone, telex, and remote access services for solar-terrestrial indices.

Telecommunications Journal

Published monthly by the International Telecommunications Union (ITU), Place des Nations, 1211 Geneva 20, Switzerland.

- Twelve-months-running-mean of *R*, *F10.7*, and *IG*
- Monthly averages of *Ri*, *F10.7*, and *IG*
- Forecasts for four to 11 months

CCIR Circular of Basic Indices for Ionospheric Propagation

Distributed monthly by the International Consultative Radioscience Committee (CCIR), ITU, Place des Nations, 1211 Geneva 20, Switzerland, prior to publication in the *Telecommunications Journal*.

- Monthly Values and Twelve-months-running-means: *Ri*, *F10.7*, *IG*, I_{F2}

Journal of Geophysical Research (blue, Space Physics)

Published monthly by the American Geophysical Union.

- Three-hourly *Kp*, *Km*, *Kn*, and *Ks*
- Daily and monthly ΣKp, *Ap*, *Cp*, *Am*, *aa*, *An*, *As*, *F10.7*, *Ri*, *Ra* for the month a quarter-year earlier.

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APPENDICES

Appendix A: Solar Terrestrial Coordinates and Coordinate Systems............8-3

Appendix B: Coordinate Conversion Software..8-9

Appendix C: Cosmic PC Software...8-11

Appendix D: Table of NSSDC IDs Included in This Report.....................8-13

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Appendix A: Solar-Terrestrial Coordinates and Coordinate Systems

A number of coordinate systems are being used for solar-terrestrial studies. The various systems are distinguished by the orientation of their axes. Except for the *B*, *L* and α, β coordinate systems, all systems are right-handed and orthogonal.

Geographic Coordinate System

In the geographic coordinate system, the positive *Z* axis is aligned northward along the Earth's spin axis. The positive *X* axis lies in the Earth's equatorial plane and points towards the Greenwich meridian.

The *geocentric* latitude of a point *P* is the angle measured at the Earth's center between the equatorial plane and a radius to *P*. The *geodetic* latitude of *P* (sometimes called the geographic latitude) is the angle between the equatorial plane and the line which passes through *P* and which is normal to the oblate ellipsoid whose surface most nearly approximates the mean sea-level surface of the Earth (i.e., the geoid). The maximum difference between geodetic and geocentric latitudes at the Earth's surface is about 0.2° and occurs near 45° latitude. The *astronomical* latitude of *P* is the angle between the equatorial plane and the plumb-bob vertical direction at *P*. The difference between geodetic and astronomical latitudes is almost everywhere less than 0.02°.

Equatorial Coordinate System

In the equatorial coordinate system, the positive *Z* axis is perpendicular to the Earth's equatorial plane (positive North), while the *X* axis points from the Earth to the Sun at the moment of the vernal equinox (or, equivalently, to the point of Aries). This is an inertial system and is sometimes referred to as the *geocentric celestial inertial coordinate system*. Because of the slow precession of the Earth's equatorial plane, an epoch date should be defined for the sake of completeness.

Right ascension is defined as the angular distance east of the vernal equinox as measured along the Earth's equator; *declination* is the angular distance north (positive) or south of the Earth's equatorial plane. Right ascension and declination are often used in specifying vector directions (as of magnetic fields) in an inertial coordinate system.

Geomagnetic Dipole Coordinate System

In the geomagnetic dipole coordinate system, the *X* and *Y* axes lie in the geomagnetic equatorial plane, and the positive *Z* axis is aligned northward along the geocentric geomagnetic dipole axis.

The positive *X* axis is defined as the intersection of the equatorial plane and the plane formed by the geographic and geomagnetic *Z* axis; it is positive pointing toward Peru/Brazil. The Earth dipole field is not centered (the magnetic center is about 500 km from the Earth's center) and the eccentricity is increasing at the rate of 2 km to 3 km per year. Nevertheless, the geocentric dipole coordinate system with a tilt angle of 11.4° gives a sufficiently good representation for most magnetospheric applications in the range 2 to 5 Earth radii.

Geomagnetic Multipole Coordinates

These coordinates are based on a spherical harmonic representations of the Earth's internal field (see the section on Magnetic Field Models [Main Field Only], pages 4-3 through 4-12). At each point the magnetic field vector ***B*** can be decomposed into its Cartesian components B_x (north), B_y (east), and B_z (vertical, up). The *magnetic declination* is the angle between the *X* axis and the horizontal projection ***H*** of the field vector ***B***. This angle is given by the deviation of a compass needle from true North. The *magnetic inclination* (short: *dip*) ψ is the angle between ***H*** and ***B***. It is the angle between the magnetic field vector and the local horizontal plane, positive when directed downward. The *dip latitude* or *magnetic latitude* Ψ is defined by the magnetic inclination (usually at 300 km):

$$\tan\Psi = \frac{1}{2}\tan\psi$$

This is the equation that relates the geomagnetic (dipole) latitude with the inclination in the case of a pure dipole field.

For worldwide mappings of ionospheric parameters, the *modified dip latitude* μ is the better magnetic latitudinal coordinate (Rawer, 1963).

$$\tan\mu = \psi / \cos^{\frac{1}{2}}\varphi$$

μ is practically identical to the *dip* ψ at low latitudes and comes nearer to the geographical latitude φ with increasing latitude.

References:

K. Rawer, *Meteorological and Astronomical Influences on Radio Wave Propagation*, B. Landmark (ed.), p. 221, Academic Press, New York, 1963.

Corrected Geomagnetic Coordinate (CGM) System

The CGM system as proposed by Hakura (1965) is based on a spherical harmonics (multipole) representation of the Earth's magnetic field. All points along a single field line have the same CGM latitude and longitude (negative sign may be used for southern latitudes). CGM is the more realistic predecessor of the simple geomagnetic (dipole) coordinate system. Calculation of CGM coordinates is quite involved and not as straightforward as the geomagnetic (dipole) transformation. CGM latitudes and longitudes are obtained by field-line tracing. Tables based on the International Geomagnetic Reference Field (IGRF) 1970 and 1980 were tabulated by G. Gustafsson (1970, 1984). CGM coordinates have been widely used for auroral investigations and studies involving magnetic conjugacy. The latest tables, however, are by now nearly ten years old. Baker and Wing (1989) note misinterpretations of conjugate points by more than 100 km. They developed a modified CGM coordinate system for the Polar Anglo-American Conjugate Experiment (PACE). Their *PACE Geomagnetic (PGM) Coordinate System* is based on the IGRF model for 1988 and is given in the form of analytical expressions depending on geographic latitude, longitude, and altitude.

References:

Y. Hakura, Tables and Maps of Geomagnetic Coordinates Corrected by the Higher Order Spherical Harmonic Terms, *Rep. Ionos. Space Res. Japan* 19, 121, 1965.

G. Gustafsson, A Revised Corrected Geomagnetic Coordinate System, *Ark. Geophys.* 5, 595, 1970.

G. Gustafsson, Corrected Geomagnetic Coordinates for Epoch 1980, in: *Magnetospheric Currents*, T. Polemra (ed.), pp. 276-283, American Geophysical Union, Washington, D.C., 1984.

K. B. Baker and S. Wing, A New Magnetic Coordinate System for Conjugate Studies at High Latitudes, *J. Geophys. Res.* 94, 9139, 1989.

Solar Magnetic (SM) Coordinate System

In the solar magnetic coordinate system, the positive *Z* axis is aligned northward along the geocentric geomagnetic dipole axis while the *X* axis lies in the plane formed by the *Z* axis and the Earth-Sun line; *X* is positive in the sunward hemisphere. *Y* is in the geomagnetic equatorial plane. Solar magnetic coordinates are recommended for those magnetospheric studies in which the main geomagnetic field is a dominant factor.

Geocentric Solar Magnetospheric (GSM) Coordinate System

In the solar magnetospheric coordinate system, the positive *X* axis points toward the Sun while the *Z* axis lies in the plane formed by the *X* axis and the geomagnetic dipole axis; *Z* is positive in the Northern Hemisphere. This coordinate system is recommended for those magnetospheric studies involving the geomagnetic tail and for others in which the overall magnetosphere configuration is a dominant factor.

Solar Ecliptic (GSE) Coordinate System

In the solar ecliptic coordinate system, the *X* and *Y* axes lie in the ecliptic plane, and the *Z* axis is perpendicular to the ecliptic plane (positive North). The *X* axis is directed toward the Sun. In terms of the equatorial coordinate system previously discussed, the *Z* axis of the solar ecliptic coordinate system has the right ascension of -90° and a declination of 66.56°.

The solar ecliptic coordinate system is recommended for studies of solar wind related interplanetary phenomena. The solar ecliptic coordinate system should not be confused with the *heliocentric ecliptic coordinate system* used in some spacecraft trajectory analyses. In the latter system, the *Z* axis is also normal to the ecliptic plane, but the *X* axis lies along the Earth-Sun line defined at the time of the vernal equinox.

B, L Coordinates, Invariant Geomagnetic Coordinates

To properly organize magnetospheric trapped particle data, McIlwain (1961, 1966) introduced the *B, L* coordinate system. *B* is the magnetic field strength at the point of interest, and *L* is a parameter which marks the individual field lines. *L* does not change along dipole field lines and changes only slightly along the real Earth magnetic field lines. It correlates to the equatorial crossing distance in Earth radii.

The advantage in the use of the *B, L* coordinates is that a particle conserving its first two adiabatic invariants mirrors at the same *B, L* values as it drifts around the Earth. Thus, in the absence of significant azimuthal gradients in particle populations such as those resulting from the South Atlantic magnetic anomaly, *B, L* coordinates organize trapped particle flux data very well. At *L*-values greater than about five, the geomagnetic field is sufficiently nondipolar so that each field line is characterized by a range of *L*-values, and the *B, L* coordinates are somewhat deficient in organizing the particle fluxes.

Useful auxiliary quantities have been defined to complement *B, L* coordinates; for example, Roberts (1964) introduced a radius variable *R* and latitude variable λ in terms of *B* and *L* by assuming dipolar relations.

Another useful variable is the invariant (geomagnetic) latitude Σ, which is defined by $\cos^2\Sigma = 1/L$. Σ is a field line Earth-intersection latitude derived from the actual *L*-value using a dipole relationship.

References:

C. E. McIlwain, Coordinates for Mapping the Distribution of Magnetically Trapped Particles, *J. Geophys. Res.* 66, 3681, 1961.

C. S. Roberts, Coordinates for the Study of Particles Trapped in the Earth's Magnetic Field: A Method of Converting from *B, L* to *R*, λ Coordinates, *J. Geophys. Res.* 69, 5089, 1964.

C. E. McIlwain, Magnetic Coordinates, in: *Radiation Trapped in the Earth's Magnetic Field*, B. M. McCormac (ed.), pp. 45-61, D. Reidel Publishing Company, Dordrecht, Holland, 1966.

C. T. Russell, Geophysical Coordinate Transformations, *Cosmic Electrodynamics*, Volume 2, 184-196, 1971.

α, β Coordinate System

The α, β coordinates, also called Euler Potentials, are constant on a given field line and satisfy $\mathbf{B}(\mathbf{r}, t) = \nabla \alpha(\mathbf{r}, t) \times \nabla \beta(\mathbf{r}, t)$. A third coordinate, usually designated by s, provides a measure of distance along a field line from some reference point. The α, β coordinates are not unique in that two α, β pairs related by a Jacobian of unity are equally valid. Some of the advantages of this system are indicated in Stern (1968); the relation of α, β to B, L is also given in this reference.

References:

D. Stern, Euler Potentials and Geomagnetic Drift Shells, *J. Geophys. Res.* 73, 4373, 1968.

Solar Zenith Angle and Declination

The solar zenith angle χ at a point P is the angle between the Earth radius through P and the line from P to the Sun. At the Earth's surface the following approximation can be used

$$\cos \chi = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos\left(\frac{\pi}{12}(t - 12)\right)$$

where λ is the geographic latitude and t the local time. The solar declination δ is the angle between the Earth-Sun line and the Earth equatorial plane and can be represented in terms of the day of year (DOY).

$$\delta/\text{degree} = -23.44 \bullet \cos\left(\frac{2\pi}{365.25}(\text{DOY} + 8)\right)$$

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Appendix B: Coordinate Conversion Software

Several software packages listed in this handbook include subroutines that convert between different coordinate systems, or calculate specific coordinates.

- International Reference Ionosphere (page 2-3):

  Geographic ⇔ Geomagnetic
  Dip, dip latitude, solar zenith angle, solar declination

- Tsyganenko Magnetic Field Model (page 4-15):

  Geographic ⇔ CGM
  Geographic ⇔ Geomagnetic
  Geographic ⇔ GSM
  SM ⇔ Geomagnetic
  GSM ⇔ GSE
  SM ⇔ GSM

  Greenwhich mean sideral time, Sun declination, and right ascension

- INVAR/NEWMAG (page 4-17): *B, L*
- ALLMAG/INVARA/LINTRA (page 4-18): *B, L*
- FELDG/SHELLG/INTELG (page 4-19): *B, L*
- NEWBL (page 4-20): *B, L*
- BILCAL/IGRF (page 4-21): *B, L*, dip, magnetic declination, B_0 (equatorial field strength)
- The software for the PACE Geomagnetic (PGM) Coordinate System can be obtained from K. B. Baker, Applied Physics Laboratory, Johns Hopkins Road, Laurel, Maryland 20707; SPAN: APLSP::BAKER.
- For more information about the α, β coordinate system and possibly computer codes, please contact D. Stern, NASA/GSFC, Code 695, Greenbelt, Maryland 20771; SPAN: LEPVAX::U5DPS.

Appendix C: COSMIC: PC Software

University of Georgia
382 East Broad Street
Athens, Georgia 30602
(404) 542-3265

Parameter: Microcomputer software

Brief Description: COSMIC was established in 1966 by NASA to provide a central office to collect the software developed under NASA funding and to make it available for reuse by industry, universities, and other governmental agencies. Currently available from COSMIC are over 1,000 computer programs, representing all areas of NASA project involvement: aerodynamics, astronautics, space sciences, computer science, engineering, lasers, geosciences, physics, mathematics, and social sciences. COSMIC's customer support staff may also be able to help locate software for special applications. The price for a specific software program (source code) is usually about several hundred dollars and the software documentation less than a hundred dollars.

Availability: A catalog of brief descriptions is issued every year.

Appendix D: Table of NSSDC IDs Included in This Report

NSSDC ID	Page	NSSDC ID	Page	NSSDC ID	Page
78-018A-01A	2-10	MN-31A	3-4	MT-32F	4-29
MG-1AA	4-8	MN-37A	3-4	MT-32G	4-29
MG-1AB	4-8	MN-61A	3-7	MT-32H	4-29
MG-1BA	4-9	MN-61B	3-7	MT-32I	4-29
MG-1BB	4-9	MN-61C	3-7	MT-32J	4-29
MG-11A	4-4	MN-61D	3-7	MT-32K	4-29
MG-12A	4-4	MN-61E	3-8	MT-32L	4-29
MG-12B	4-10	MN-62A	6-3	MT-32M	4-29
MG-12C	4-12	MT-2AA	4-22	MZ-14A	5-5
MG-12D	4-10	MT-2AB	4-22	PG-11A	4-16
MG-13A	4-5	MT-11B	4-22	PG-12A	4-18
MG-16A	4-5	MT-12B	4-22	PG-12C	4-18
MG-17A	4-6	MT-13B	4-22	PG-12D	4-18
MG-18A	4-6	MT-14B	4-22	PG-12E	4-18
MG-19A	4-7	MT-15B	4-22	PG-13E	4-19
MG-21A, B	4-14	MT-16B	4-22	PG-16A	4-17
MG-22A	4-13	MT-17B	4-22	PG-18A	4-20
MG-23A	4-13	MT-18B	4-22	PG-18B	4-20
MG-24A	4-14	MT-18C	4-22	PG-18C	4-11, 4-21
MG-25A	4-15	MT-18F	4-22	PG-18D	4-15
MI-91A	2-4	MT-18H	4-22	PG-18E	4-15
MI-91C	2-3	MT-21B	4-22	PG-21A	4-19
MI-91D	2-3	MT-22B	4-22	PT-11A	4-25
MI-91E	2-3	MT-23A	4-22	PT-11B	4-26
MI-91F	2-3	MT-24B	4-22	PT-11C	4-26
MI-91G	2-5	MT-25B	4-22	PT-12A	4-27
MI-92C	2-8	MT-26D	4-22	PT-15A	4-28
MI-92D	2-9	MT-28B	4-22	PT-16A	4-28
MI-93A	2-18	MT-32A	4-29	PX-21A	4-27
MI-93B	2-15	MT-32B	4-29	RS-12B	5-4
MI-94A	6-3	MT-32C	4-29	SM-41B	7-10
MN-17A	3-5	MT-32D	4-29		
MN-30A	3-4	MT-32E	4-29		