Data Synthesis and Display

Programs for

Wave Distribution Function Analysis

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Contents

Abstract

At the National Space Science Data Center (NSSDC) software has been written to synthesize and display artificial data for use in developing the methodology of wave distribution analysis. This software comprises two separate interactive programs, one for data synthesis and the other for data display.

1. Introduction

When the fields of natural radio waves are observed and measured by instruments on spacecraft, the experimenter often wants to know in what directions the waves are traveling. It helps if data from the wave receivers can be analyzed to yield sky maps showing how the intensity of the waves varies as a function of direction over the celestial sphere, like the maps that astronomers make.

At low frequencies, however, the sky maps used by space radiophysicists differ from those used by astronomers. The differences concern, among other things, the definitions of the direction and intensity of a wave.

One difference concerning the direction is simply a matter of convention. Optical and radio astronomers are accustomed to sky maps in which the properties of the waves are plotted versus direction of arrival. This is the direction from which the waves are coming, or in other words, the direction of the line of sight from the observer to the source of the waves. In radiophysics, however, the behavior of waves is commonly discussed in terms of the direction of propagation, which is the direction in which the waves are going, i.e., the opposite of the direction of arrival. Hence, radiophysicists use the direction of propagation as the independent variable for sky mapping.

The other main differences are physical matters. They are due to the presence in space of plasma permeated by magnetic fields.

At frequencies so low that the plasma affects the waves, the direction of propagation of their wavefronts, or *wave normal* direction, is not the same as the direction of propagation of their energy, or *ray* direction; the relation between these two directions has been explained by many authors [1-3]. In making sky maps, radiophysicists prefer to use the wave normal direction because it identifies a wave unambiguously. This means that for a given wave normal direction there can be only one ray direction, whereas for a given ray direction there may be two or more, or even, in some special cases, infinitely many possible wave normal directions.

To specify the direction of the wave normal, a set of right-handed Cartesian axes $Oxyz$ is adopted with Oz parallel to the local vector B_0 of the Earth's magnetic field, and Ox parallel to the projection into the plane perpendicular to B_0 of the radius vector from the center of the Earth to the position of the spacecraft. Then the direction of the wave normal can be specified by the polar angle θ that it makes with the z-axis, together with the azimuthal angle ϕ measured right-handedly around the z-axis from the x-axis as origin (See Figure 1 below).

Now consider the wave intensity. For waves in free space, it is generally measured by the wave power per unit area or *flux*, but this is a vector quantity associated with the ray direction. For a single coherent wave of constant amplitude, with a unique frequency and a unique wave normal direction, propagating in a plasma, the wave energy per unit volume or *energy density* is a more convenient

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measure. Natural radio waves, however, are more often random than coherent, and for random waves the proper measure is the energy density per unit frequency range and unit solid angle of wave normal direction. This scalar quantity, considered as a function of frequency and of wave normal direction, is known as the *wave distribution function* (WDF).
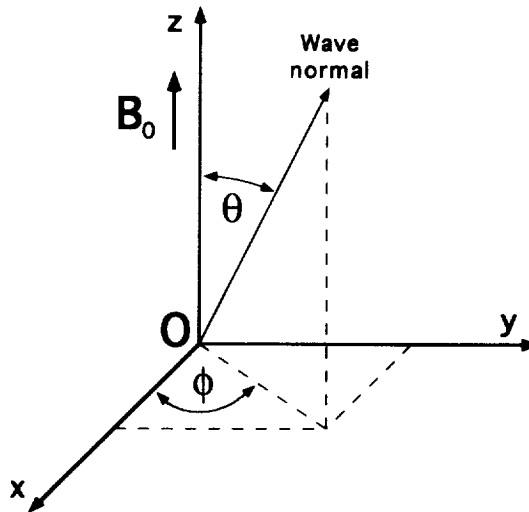

Figure 1. Coordinate System

A radio sky map is a graphic display of a WDF versus wave normal direction at a fixed frequency. Customarily, two polar plots are used, one for each hemisphere, with θ as the radial and ϕ as the azimuthal coordinate. Contour lines are used to display the WDF quantitatively. An example is given in Figure 2 below . The circle forming the outer boundary of the map corresponds to the plane perpendicular to B_0, here called the *equator*. The absence of data in a zone centered on the equator is another effect of the plasma, which at low frequencies forbids propagation at values of θ (or of 180° - θ if θ > 90°) larger than a certain value known as the *resonance angle*.
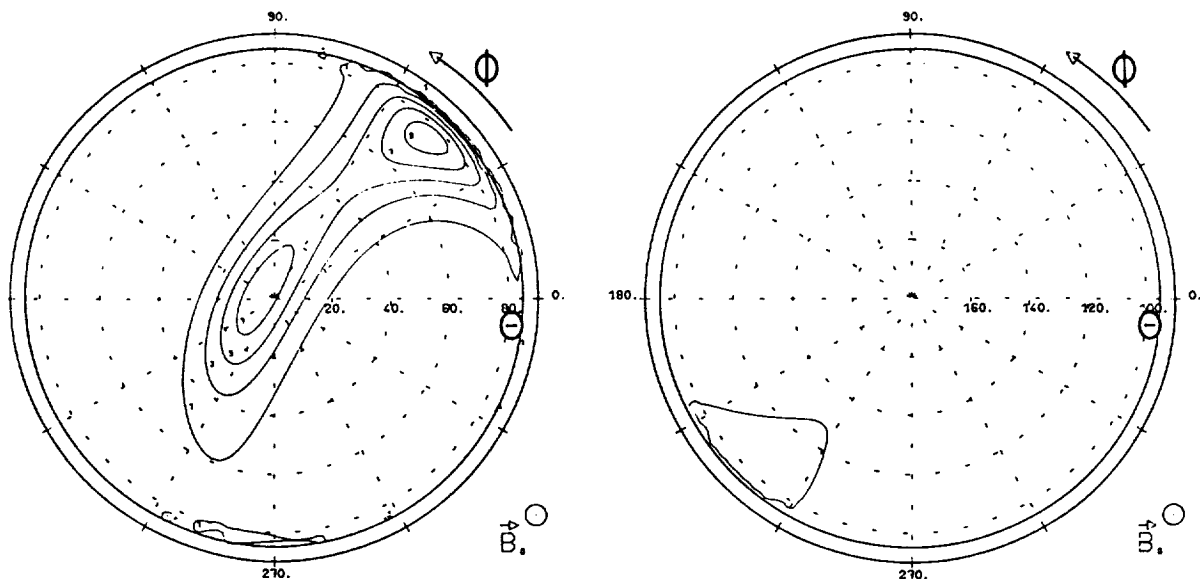

Figure 2. Sky Map of an Experimentally Determined WDF [17]

In the radio sky map of Figure 2 above, it is obvious that the angular resolution is very poor indeed compared with what optical astronomers achieve. This is due to the difficulty of making directive observations of waves in space at low frequencies, where the wavelengths are much greater than the dimensions of any antennas that can be deployed from a spacecraft. With a single spacecraft, the best one can do is make local measurements of the electric and magnetic field vectors of the waves, then perform a sophisticated data analysis yielding some degree of "super-resolution." The resulting sky maps are relatively crude, but even so they are useful for scientific purposes.

The methodology for analyzing local measurements of radio wave fields in space to obtain the corresponding wave distribution functions is known as WDF analysis. General methods of WDF analysis exist, based on the principle of maximum entropy [4-6]. Some other methods are suited only to special cases where the waves are coming from just a few point sources [7,8]. There is scope for improvement in all of these methods, however, and new ones may be needed [9].

For the further development of WDF analysis, it is essential to have a means for synthesizing artificial data. The developer must be able to create artificial sky maps of some fairly general form, and synthesize the data that a spacecraft could observe in the presence of wave fields with the corresponding WDFs. These artificial data can be analyzed by the method under development and the resulting WDFs plotted as sky maps, which can then be compared with the originals to evaluate the performance of the method.
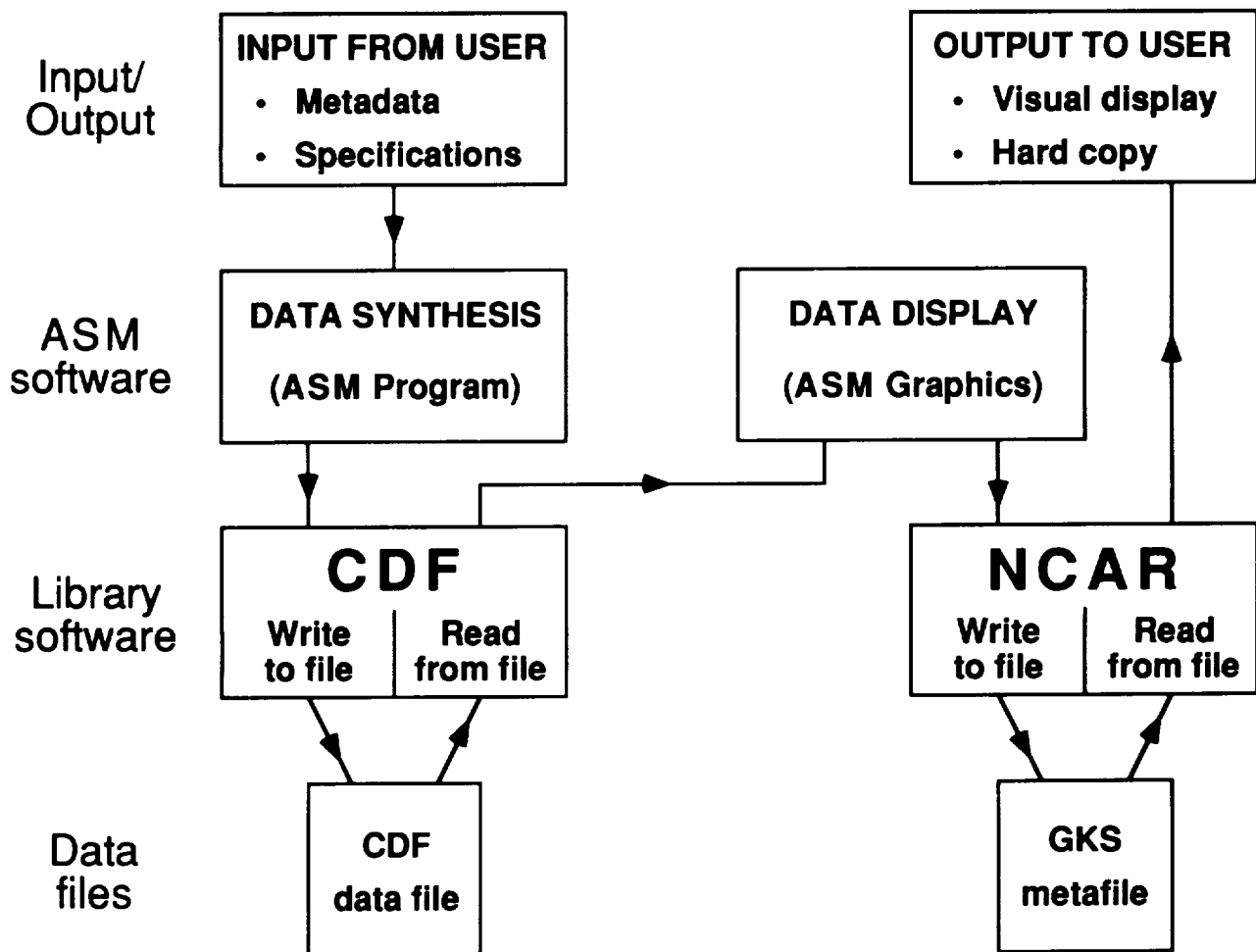

Figure 3. Flowchart for the synthesis and display of an artificial sky map.

The present report describes a set of software written for this purpose. As shown in the flowchart of Figure 3 above, it consists of two programs: The first, called the Artificial Sky Map (ASM) Program, is for data synthesis, while the second, called ASM Graphics, is for data display. At the start the user enters the specifications for an artificial sky map to the ASM Program through an alphanumeric terminal, while at the finish the ASM Graphics program displays the map on a graphics terminal or a laser printer; the two terminals can, of course, be the same. Both programs are interactive.

Besides this pair of special-purpose programs, two library software packages are utilized, namely the NSSDC Common Data Format (CDF) scientific data base software [10], and the National Center for Atmospheric Research (NCAR) Graphics software [11] which uses the standard Graphical Kernel System (GKS). Data are transferred from the ASM Program to ASM Graphics via a CDF data file, and from ASM Graphics to the display terminal via a GKS metafile (See Figure 3 above). ASM Graphics can also accept CDF files created by the WDF analysis programs.

The plan of this report is as follows: Section 2 explains what experimental data are required for WDF analysis and how they must be reduced beforehand; section 3 presents the basic equation used for synthesizing artificial data; section 4 describes the data synthesis program and section 5 the data display program; section 6 gives some technical details of the software, including how it may be obtained, while the final sections 7 and 8 contain the acknowledgments and the references, respectively.

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2. *Data Reduction*

When observing natural low-frequency radio waves from a single spacecraft, the best that can be done is to measure the three components E_x, E_y, and E_z of the electric field vector **E** together with the three components H_x, H_y, and H_z of the magnetic field vector **H**. Multiplying **H** by the wave impedance Z_0 of free space turns it into an equivalent electric field, and by this means the entire electromagnetic field can be represented by a six-component generalized electric field vector $\mathscr{E}$, the components of which are

$$\left.\begin{array}{lll} \mathscr{E}_1 = E_x & \mathscr{E}_2 = E_y & \mathscr{E}_3 = E_z \\[2em] \mathscr{E}_4 = Z_0\,H_x & \mathscr{E}_5 = Z_0\,H_y & \mathscr{E}_6 = Z_0\,H_z \end{array}\right\} \tag{1}$$

A set of spacecraft data normally consists of measurements of some or all of the six components of $\mathscr{E}$, made in a frequency band of width B over a time interval of duration T; here all six components will be assumed to have been measured.

If these data are of good quality and are random, they will be suitable for WDF analysis after some preliminary processing. The first step is to divide the set into sub-bands of width ΔB within which the spectra of the data are effectively uniform and into sub-intervals of duration ΔT within which their statistics are effectively stationary. Then the data from each one of these sub-regions of the frequency-time plane are processed to yield an estimate $\hat{S}$ for the spectral matrix S of the generalized electric field, at the center frequency ω and center time t of the sub-region concerned. The elements S_{ij} of the matrix S are the auto-power spectra (if i = j) of the six field components, and the cross-power spectra (if i ≠ j) of the 15 pairs of different field components. This processing, which is performed by standard procedures [12], greatly reduces the amount of data. The initial data set, consisting of six waveforms of bandwidth B and duration T, is reduced to a set of estimates $\hat{S}_{ij}$ for the matrix elements S_{ij} with relative accuracies of about $(\Delta B\,\Delta T)^{-1/2}$, a total of 36 independent numbers. These reduced data are the input for the WDF analysis, which should produce as output an estimate for the WDF of the original wave field at the frequency ω and time t.

The artificial data are synthesized at the level of the spectral matrix S, which may be considered as an ensemble average of the reduced data matrix $\hat{S}$, taken over all possible data sets consistent with the given WDF. Thus, the synthetic data are free from the statistical fluctuations, caused by the non-infiniteness of ΔB and ΔT, that affect real data from spacecraft; they are also free from noise. When data from the ASM Program are used for testing new methods of WDF analysis, artificial errors in the form of both fluctuations and noise are introduced optionally, in a controlled way, by dedicated routines imbedded in the analysis software.
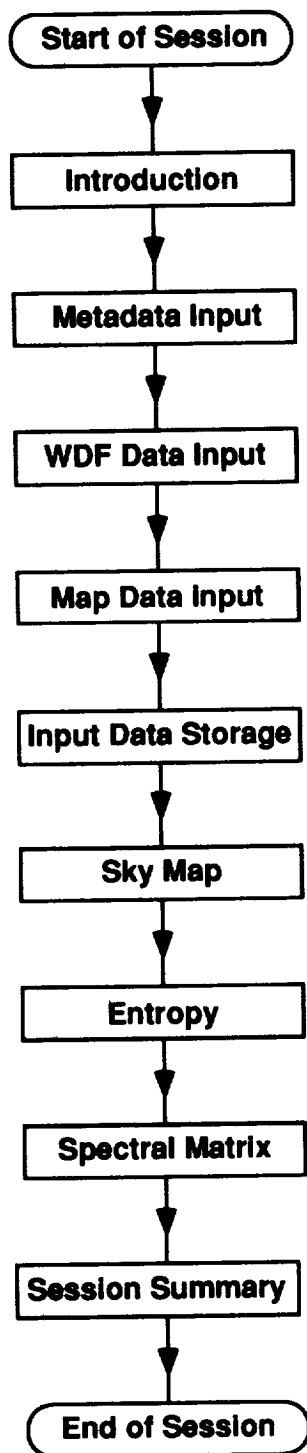
3. Basic Equation

From specifications entered by the user, the ASM Program tabulates the WDF and computes from it the corresponding spectral matrix S, the elements of which are related to the WDF by the integral equation
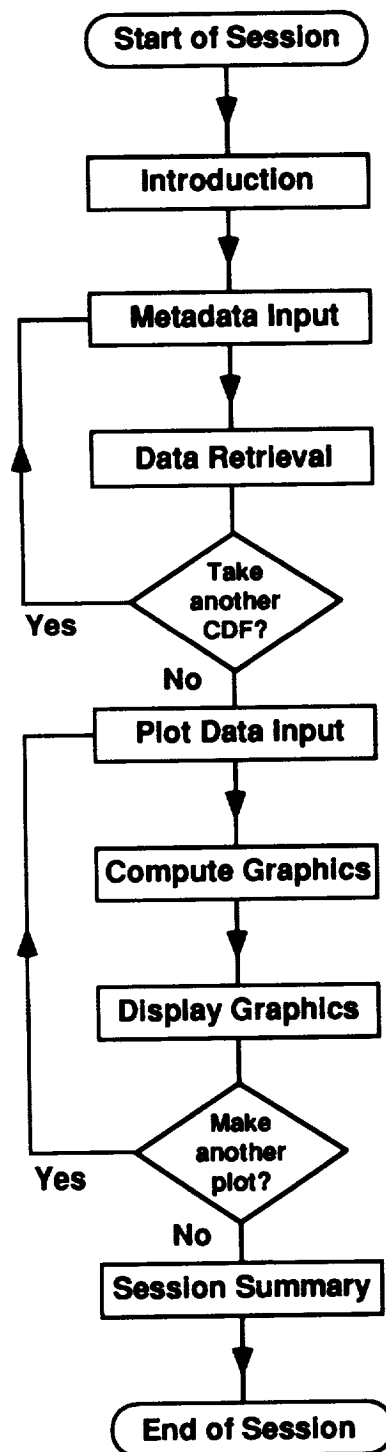
$$S_{ij}(\omega) = \pi/2 \oiint F(\omega,\theta,\phi)\, a_{ij}(\omega,\theta,\phi)\, d\sigma \qquad (2)$$

In the integrand, F is the WDF while the kernels a_{ij} are known functions of the angles θ and ϕ; for those directions (θ,ϕ) in which propagation is forbidden, the WDF is zero. The integral is taken over the 4π range of solid angle of which $d\sigma = d(\cos\theta)\, d\phi$ is an element [13].

The functional forms of the integration kernels a_{ij} are governed by the properties of the ambient plasma medium. Approximate expressions for them have been published by Storey and Lefeuvre [14]; an error has been corrected by Lefeuvre et al. [15].

Flowchart (a) ASM Program

- Start of Session
- Introduction
- Metadata Input
- WDF Data Input
- Map Data Input
- Input Data Storage
- Sky Map
- Entropy
- Spectral Matrix
- Session Summary
- End of Session

Flowchart (b) ASM Graphics

- Start of Session
- Introduction
- Metadata Input
- Data Retrieval
- Take another CDF? — Yes → Metadata Input; No ↓
- Plot Data Input
- Compute Graphics
- Display Graphics
- Make another plot? — Yes → Plot Data Input; No ↓
- Session Summary
- End of Session

(a) ASM Program

(b) ASM Graphics

Figure 4. Operations Performed by the Two Programs

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4. Data Synthesis

The ASM Program synthesizes artificial data by the sequence of operations shown in Figure 4a above. The program has nine major sections, namely Introduction, Metadata Input, WDF Data Input, Map Data Input, Input Data Storage, Sky Map, Entropy, Spectral Matrix, and Session Summary.

The Introduction acquaints the user with the program. A single paragraph explains its purpose, while another outlines the interactions that the user should expect.

The Metadata Input section enables the user to enter identifying personal information. The metadata currently accepted are the user's name, the user's institute or other professional affiliation, and the date on which the session is taking place. The user is also prompted to enter a name for the artificial sky map; this name is used as the title for the CDF files in which all the artificial data are stored and also for the summary text file. The program examines whether any CDF files with this title exist already and, if so, offers the user the choice of either deleting those files or supplying another name.

The WDF Data Input section serves for entering all the parameters that jointly define the shape of the model WDF. They comprise firstly some parameters governing the influence of the space plasma and magnetic field on the waves and secondly the parameters of the wave sources.

In the approximations used here, the influence of the ambient plasma on the waves depends on the relative values of three characteristic frequencies: the electron plasma frequency, which characterizes the plasma; the electron gyrofrequency, which characterizes the magnetic field; and the frequency of the waves themselves. After these parameters have been entered, the program computes from them the resonance angle θ_{res}. The half-width in θ of the range of directions around the equator within which the waves cannot propagate is $90° - \theta_{res}$. The values of θ at the edges of this forbidden zone are displayed so that the user can avoid placing any wave sources there.

The model adopted for the WDF provides for wave sources of two kinds: point sources (like stars) and extended sources (like nebulae). Each point source is characterized by three parameters, namely its direction angles θ and ϕ and its integrated intensity. For an extended source, the profile of intensity versus position is approximately Gaussian along any great circle passing through the center of the source, and the contours of equal intensity are approximately elliptical. The profile would be exactly Gaussian and the contours exactly elliptical were it not that the program modifies the shape of the source so that the WDF falls smoothly to zero at the edges of the forbidden zone. Each extended source is characterized by six parameters, which include the angles θ and ϕ for its center where it is most intense, and the value of its maximum intensity. The remaining three parameters specify its extension in terms of the properties of the contour where the intensity is $\exp(-1/2) = 0.61$ times the maximum value: They are the half-length of the major axis of the ellipse, the direction of this axis relative to the local meridian (i.e., the radial line of constant ϕ passing through the center of the source), and the axial ratio. Up to ten point sources and ten extended sources can be accommodated in the model.

If the sky map of the WDF is to be tabulated for future visualization, the Map Data Input section allows the user to enter the specifications for the map grid, which is uniform in both θ and ϕ. The user specifies the number of equal intervals into which the range of each of these variables should be divided. These are the last of the input data, apart from the user's responses to options.

Next, the Input Data Storage section of the program stores the metadata, the WDF data, and the map specifications (if any), by writing them to a CDF file. Then, if the user has asked for a sky map to be tabulated, the Sky Map section computes the WDF at the centers of the map grid cells and stores the resulting table in the CDF.

Optionally, the Entropy section computes and stores this quantity, which is a nonlinear functional used in some WDF analysis algorithms (see section 1). Different authors use different expressions for the entropy, and computations are made for two of these. The relation between them involves the mean value of the WDF, which is proportional to the total energy density of the wave field, so the mean is computed and stored as well. This option is offered only if the model WDF contains no point sources, since the entropy of a point source is infinitely negative.

Again as an option, the Spectral Matrix section computes these artificial data and stores them in the CDF. The double integrals (2) are evaluated to a nominal accuracy of one part in 10^6 by Romberg integration [16]. A final option is to have the Session Summary section create a text file containing all the input data, including the previous options that the user took.

5. *Data Display*

The ASM Graphics program, which plots the artificial WDFs as sky maps, has a structure similar to that of the ASM Program (see Figure 4b above). It has seven major sections: Introduction, Metadata Input, Data Retrieval, Plot Data Input, Graphics Computation, Graphics Display, and Session Summary.

The first two sections and the last are very similar to the corresponding ones in the ASM Program, except that in the Metadata Input section the user is prompted to enter the title of a CDF that already exists and contains the data for display. The program checks that there is indeed a CDF with this title in the working directory. If not, it displays a warning and allows the user either to change the title or to exit from the program and bring the wanted CDF file into this directory.
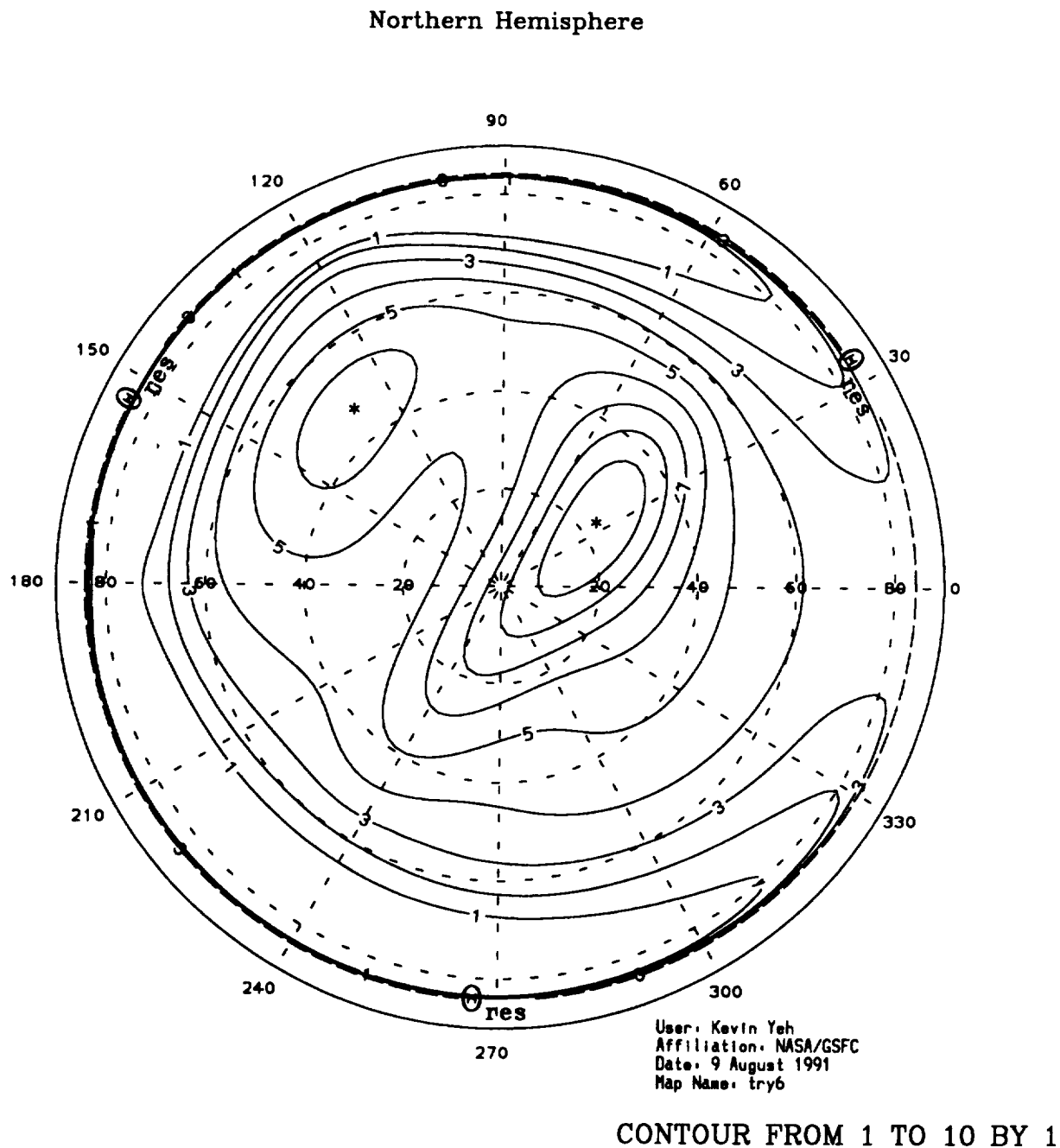
The Data Retrieval section retrieves the data from the selected CDF using procedures supplied in the CDF software library. First, it retrieves and displays the metadata that describe the contents of the file; then it prompts the user either to confirm that this is indeed the wanted file, or to return to the Metadata Entry section and select a different title. If the user confirms the file, the program then retrieves its main contents.

Next, in the Plot Data Input section, the user provides some specifications for the sky map. The major decision is the choice of the hemisphere from which to take the WDF data for plotting; the options are the Northern Hemisphere data (i.e., those for $\theta < 90°$), the Southern Hemisphere data ($\theta > 90°$), and the sum of the data from both hemispheres. After this, the user is asked to accept or reject the printing of certain enhancements to the map; these include the metadata, the contouring information, a circle at the resonance angle θ_{res}, and a frame surrounding the polar plot of the WDF.

Graphics Computation is the largest section of the program. It extracts data from the CDF in the light of the user's options and generates plotting instructions for the map with the help of routines from the NCAR Graphics library, in particular some contouring routines from a package named CONPACK. First, the required WDF data are extracted, then processed if necessary, according to the hemisphere option mentioned above. Then the instructions for the contour plot are generated; this plot concerns only the contribution to the WDF from the extended sources. The next set of instructions is for plotting the positions of the point sources. After this, the program makes the instructions for plotting the polar grid background for the contours, for printing identifiers such as a serial number and the hemisphere of the plot, and for printing any enhancements that the user selected. The output from this section is a GKS graphics metafile with a complete set of instructions for displaying the required sky map on a laser printer or a terminal screen.

The Graphics Display section reads these instructions from the metafile and sends them to either of the devices on which the map can be displayed and viewed. Both require the use of a metafile translator, specifically the one called *ctrans* in the NCAR Graphics library, to convert data from the metafile to a format usable by the printer or the terminal. After the map has been displayed, the program asks

whether the user wishes to plot the data in any of the other possible ways, and if so it returns to the start of the Plot Data Entry section. Otherwise it continues through the Session Summary section then terminates the session. An example of an artificial sky map plotted by this program is given in Figure 5 below.

Northern Hemisphere

User: Kevin Yeh
Affiliation: NASA/GSFC
Date: 9 August 1991
Map Name: try6

CONTOUR FROM 1 TO 10 BY 1

Figure 5. Example of an Artificial Sky Map

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6. *Technical Aspects*

Both the ASM Program and the ASM Graphics program are written in Fortran 77. They have a top-down structure and are amply commented. Their major sections occupy "Level 1" subroutines, which control all operations dealing with their specific tasks. In each subroutine, all major variables are listed and defined. The subroutines are self-contained and use no "common" variables. These features make it easy for the authors and other users to modify the programs if necessary.

The ASM Program exists in two versions: one currently runs on a VAX™ 9410 mainframe under Version 5.4-3 of the VMS™ operating system, using the VAX Fortran V5.5 compiler; the other runs on a Sun™ 4/280 workstation under Unix™ (SunOS™ V4.1.1), using Sun Fortran V1.3.1. The ASM Graphics program exists only in the latter version. By means of the File Transfer Protocol (FTP), CDFs created by the VMS version of the ASM Program can be transferred electronically to the Unix system, where the ASM Graphics program can read them and display their contents. The display uses the Sunview™ window environment.

Users of VAX/VMS systems may obtain the ASM Program and its descriptive documentation in either of two ways: via anonymous FTP from the directories [ASM.PROG21] and [ASM.DOC] in the "anonymous" account on ncf.gsfc.nasa.gov (128.183.36.23); and via the NASA Science Internet (NSI, formerly SPAN) by copying the contents of these two directories, the full names of which are NCF::ANON_DIR:[ASM.PROG21] and NCF::ANON_DIR:[ASM.DOC]. A specimen CDF created using the ASM Program and titled "Example_1" is available, together with the corresponding summary text file, in the directory NCF::ANON_DIR:[ASM.CDF].

Users of Unix systems may obtain the ASM Program, the ASM Graphics program, and the documentation for both of them by FTP from the "anonymous" account on ncgl.gsfc.nasa.gov (128.183.10.238). The relevant files are in the directories pub/asm/prog31, pub/asm/graph11, and pub/asm/doc. The specimen CDF "Example_1" and its summary text file are in the directory pub/asm/cdf. If the ASM Graphics program is run with this CDF as input and the sky map for the Northern Hemisphere is plotted, the result should be the sky map shown in Figure 5 above.

These two programs use Version 2.1 of the CDF software which is obtainable at no charge from the NSSDC Coordinated Request and User Support Office. They also use Version 3.01 of the NCAR Graphics software, and this may be obtained from the User Services Section of the Scientific Computing Division at the National Center for Atmospheric Research, in Boulder, Colorado.

7. Acknowledgments

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