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An integrated analysis platform merging SuperDARN data within the THEMIS tool developed by ERG-Science Center (ERG-SC)

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Abstract The Energization and Radiation in Geospace (ERG) mission seeks to explore the dynamics of the radiation belts in the Earth's inner magnetosphere with a space-borne probe (ERG satellite) in coordination with related ground observations and simulations/modeling studies. For this mission, the Science Center of the ERG project (ERG-SC) will provide a useful data analysis platform based on the THEMIS Data Analysis software Suite (TDAS), which has been widely used by researchers in many conjunction studies of the Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft and ground data. To import SuperDARN data to this highly useful platform, ERG-SC, in close collaboration with SuperDARN groups, developed the Common Data Format (CDF) design suitable for fitacf data and has prepared an open database of SuperDARN data archived in CDF. ERG-SC has also been developing programs written in Interactive Data Language (IDL) to load fitacf CDF files and to generate various kinds of plots−not only range-time-intensity-type plots but also two-dimensional map plots that can be superposed with other data, such as all-sky images of THEMIS-GBO and orbital footprints of various satellites. The CDF-TDAS scheme developed by ERG-SC will make it easier for researchers who are not familiar with SuperDARN data to access and analyze SuperDARN data and thereby facilitate collaborative studies with satellite data, such as the inner magnetosphere data provided by the ERG (Japan)−RBSP (USA)−THEMIS (USA) fleet.

Keywords **ERG Science Center, SuperDARN, database, data analysis software, THEMIS, Common Data Format**

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1 Introduction

The Energization and Radiation in Geospace (ERG) project will explore how relativistic electrons in the radiation belts are generated during space storms. The ERG project is the synergetic efforts of three research elements: ERG satellite observation, ground-based network observation, and simulation/modeling studies. The satellite observation will provide *in situ* measurements of particle and electric/magnetic fields in the inner magnetosphere, while the remote sensing by ground-based observations using, for example, ionospheric radars, magnetometers, optical instruments, and radiowave receivers will provide spatially larger-scale profiles of geospace. These observations will be compared extensively with modelings/simulations that reproduce important physical processes. Close collaboration of the three approaches is a key to comprehensively understanding rela-

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tivistic electron generation/loss processes resulting from cross-energy coupling in which different plasma populations are dynamically coupled with each other and the background fields. A preliminary concept study for the ERG project has been reported[1] and a more recent review of the details of the project has been published separately[2].

To promote and manage the scientific activities of the ERG project, the Science Center of the ERG project (ERG-SC) has been established. One of the important tasks of ERG-SC is to realize such a trinity collaboration and thereby maximize scientific outcomes. Until the ERG satellite joins this collaboration with its launch in 2015, ERG-SC is supposed to develop the remaining two elements of the project. In the present report, we focus on our efforts of incorporating SuperDARN radar data into our integrated data analysis framework, which is crucial to realizing the scientific goals of the ERG project.

The Super Dual Auroral Radar Network (SuperDARN)[3] is an international research collaboration that develops a world-wide network of ground-based coherent-scatter radars that operate in the high-frequency (HF) band. In this radar system, the backscatter of transmitted pulse sequences is processed to produce multi autocorrelation functions (ACFs) and basic parameters, such as backscatter power, line-of-sight Doppler velocity, and spectral width, which are deduced by fitting the ACFs. The fitted parameters are archived using the original data format called fitacf.

SuperDARN radars are very powerful tools suitable for diagnosing bulk motions of plasma mainly in the E- and F-layer ionosphere over a range of a few thousand kilometers. Their continuous operation and large-scale coverage in local time realized by the radar network provide us with detailed profiles of the evolution of ionospheric plasma motions[4] and global characteristics of ionospheric convection[5]. In addition, SuperDARN observations have played a crucial role in research on Magnetohydrodynamics (MHD) waves in the ultra low frequency (ULF) range, substorms, gravity waves, high-latitude plasma structure, and ionospheric irregularities[6]. In particular, the spatial distribution of Pc5 pulsations can be obtained[7-8], which would be important in understanding the radial diffusion of radiation belt particles.

The radars were originally constructed around magnetic latitudes of ~60 deg, looking toward the auroral zone and polar cap. Beginning in 1999 with the deployment of the first mid-latitude radar in Tasmania, the recent expansion of SuperDARN toward mid-latitudes forms an extensive coverage of sub-auroral regions that couple with the inner magnetosphere in the Northern Hemisphere. Figure 1 shows the field-of-view coverage of all SuperDARN radars in the Northern (a) and Southern (b) Hemispheres as of August 2012. A dense coverage of the mid-latitude to sub-auroral region in Northern America extending to the Russian Far East (covered by the field-of-view of the Hokkaido radar located at "HOK") has been developed as shown by orange-colored fan-shaped fields of view in Figure 1.

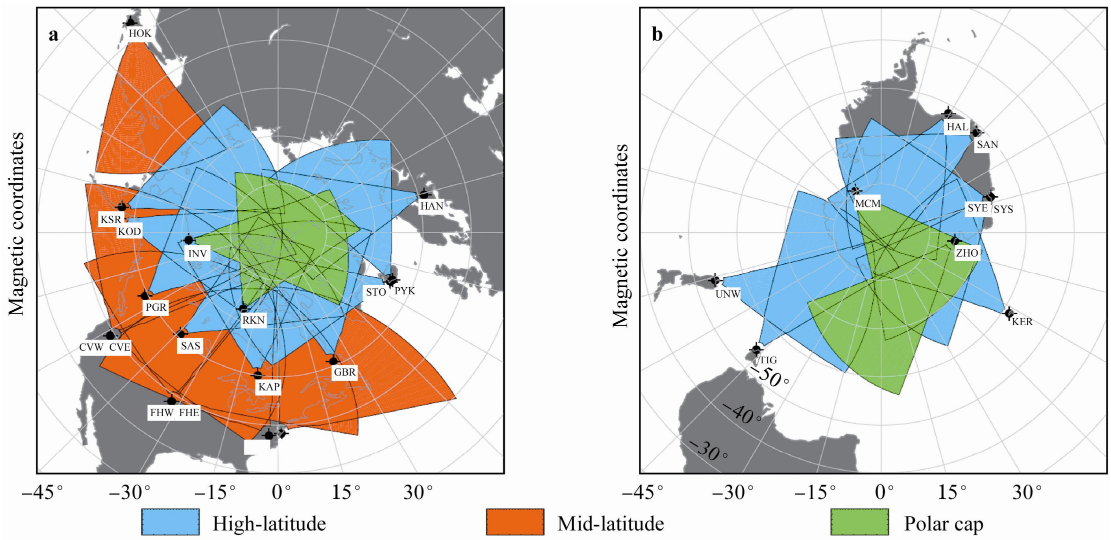

Figure 1 Field of view of all SuperDARN radars in both hemispheres as of August 2012.

An important strategy of the ERG project is to strongly associate ERG satellite observations and various kinds of ground-based observations. In particular, the extensive coverage of ionospheric flows by SuperDARN is crucial to understanding single-point measurements obtained by the satellite in the context of macroscopic flows/electric fields associated with bulk motions of plasma and/or MHD waves in the magnetosphere-ionosphere coupled system. For this purpose, as illustrated in Figure 2, the combination of mid-latitude radars and the ERG satellite has great potential for detailed conjugate observations of the inner magnetosphere–sub-auroral ionosphere region[4].

Regarding the radiation belt dynamics, the coordinated observations of the ERG satellite and SuperDARN are expected to play an important role in studies on ultra-low-frequency waves in the Pc5 range. The excitation of Pc5

ULF waves in the magnetosphere is one of the mechanisms responsible for the radial diffusion of MeV electrons in the inner magnetosphere via the drift resonance[9]. Although the drift resonance requires a large-scale wave structure distributed over the entire local time in the inner magnetosphere, recent studies have revealed that Pc5-range wave activities have more localized structures[10]. To understand the spatial-temporal evolution of Pc5 waves more comprehensively and their actual contribution to the acceleration/loss of radiation belt particles during a particular magnetic storm event, we have to know both detailed wave characteristics in the inner magnetosphere and the latitudinal/local time structure of the wave activities on the ground at the same time. This kind of coordinated measurement is made possible by ERG-SuperDARN conjunctions.

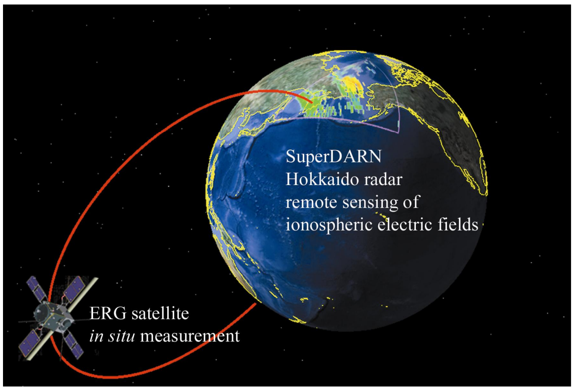

Figure 2 Schematic illustration of conjugate observations of the inner magnetosphere by the ERG satellite and the sub-auroral ionosphere by the SuperDARN Hokkaido radar.

Dynamical features of a large-scale convection electric field are also important since the spatial distribution of plasmaspheric and ring current particles, which are dominant plasma populations in the inner magnetosphere, is significantly affected by a convection electric field during storm events. Past studies suggest that the convection electric field can be highly variable and spatially structured in association with the ring current distribution[11-12]. *In situ* measurement by satellites provides us with detailed information on varying electric fields and particle profiles. However, satellite observations by themselves cannot tell what spatial or temporal resolution those observed variations actually are. In this respect, conjugate observations with the ERG satellite and SuperDARN will be of great help in resolving the “spatial or temporal” issue.

To fulfill these goals from a technical point of view, we have been preparing a database and data analysis platform to combine all kinds of ground-based observational data including SuperDARN data that has better affinity than the satellite data. One effort is the development of the Common Data Format (CDF) database of common time fitacf data and another is the creation of data analysis tools based on the THEMIS Data Analysis Software suite (TDAS) developed for the THEMIS mission[13].

In the present paper, we describe the development of the CDF database and the common data analysis platform designed by ERG-SC. The following section details the metadata and data variables stored in common time fitacf CDF files designed by ERG-SC and describes how these data files are archived and then made available to users online. Data analysis software developed by ERG-SC is briefly presented. Finally, we discuss future work regarding ERG-SC activities.

2 CDF database of common time fitacf data

Among a number of scientific data file formats, we adopted the CDF (http://cdf.gsfc.nasa.gov/) to archive fitacf data obtained by SuperDARN observations. CDF is a self-describing data file format developed and maintained by the National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC). There are several reasons for using CDF as a data file format. First, this format has been widely used to archive data by many past and on-going satellite missions in the solar-terrestrial physics community. Adopting this format allows us to use various technologies already established. One of these technologies is easy, useful interfaces with which to access CDF data included in various free and commercial software applications. Therefore, distributing data files in CDF provides a more ubiquitous framework with which to analyze the data at the end-user side. Another merit of archiving with CDF is that each data file can hold its own metadata (various kinds of meta-information describing data) and deliver them to users. The metadata are included as global attributes in CDF files. The global attributes and data variables described below have been designed by ERG-SC in close collaboration with Japanese SuperDARN groups. The CDF design was first applied to data of radars operated by the Japanese groups (Hokkaido, King Salmon, Syowa East, and Syowa West) and then extended to all radars to convert fitacf data to CDF files.

The entire list of global attributes is given in Table 1. Among the global attributes, those marked with an asterisk (*) are global attributes that the International Solar-Terrestrial Physics/Inter-Agency Consultative Group (ISTP/IACG) standards require or recommend to include in CDF files, and they are used in the categorization of data sets by the CDAWeb database (http://cdaweb.gsfc.nasa. gov/). These attributes provide general information on the data set, such as the observation project name, brief description of the data, and contact information of principal investigator (PI). Most importantly, the data policy statements for SuperDARN data are included in the “Rules_of_use” attribute. This attribute includes the official data policy statement written in the SuperDARN PIs’ agreement followed by specific notes for each radar.

ERG-SC has added its own attributes to the CDF files as listed below the ISTP/IACG standard attributes in Table 1. These attributes include the RST_version and fitacf_version attributes. These are version numbers of the program libraries used to generate the original fitacf files. Since these libraries will continue to be updated in the future as will the CDF files, we have to be able to trace back to the original fitacf data corresponding to the data in the CDF files. For a similar reason, the rbposlib version is stored in the rbposlib_version attribute. This attribute gives the version of the rbpos library that generated the position table of radar pixels stored as a data variable in the CDF files.

Table 1 Global attributes (metadata) in common time fitacf CDF

Attribute Name	Description
Project*	Name of the project holding the ownership of data. “SD>Super Dual Auroral Radar Network” is set
Discipline*	Science discipline/subdiscipline in the ISTP/IACG standards. “Space Physics>Magnetospheric Science” is set
Source_name*	Name of the mission or investigation under which data are obtained. “SD>Super Dual Auroral Radar Network” is set
Data_type*	Type of the data in CDF file. “fitacf_l2>Fitacf level 2 data” is set
Descriptor*	Name of instrument that collects data. Here the radar name (for example, “HOK>SuperDARN Hokkaido HF radar” for the Hokkaido radar) is set
Data_version*	Version number of data stored in CDF file
Title*	Title for the data set. For example, “SuperDARN Hokkaido HF radar Fitacf data” is set for the Hokkaido radar
Text*	Description for the data set
Generated_by*	The generating data center/group. “Solar-Terrestrial Environment Laboratory, Nagoya University” is set for the Hokkaido radar
Generation_date*	Date on which a data file was created
MODS*	The history of modifications made to the CDF data set
ADID_ref*	The control authority identifier, currently being left blank
Logical_file_id*	Name of the CDF file using the ISTP naming convention. “SD_FITACF_L2_” is set
Logical_source*	Source_name, data_type, and descriptor information, originally used by NASA/CDAWeb. Currently set the same as Logical_file_id
Logical_source_ description*	The full words associated with the Logical_source. For example, “SuperDARN Fitacf Level 2 data for the Hokkaido radar” is set for Hokkaido radar data CDFs
PI_name*	Name of the principal investigator (PI) of a radar
PI_affiliation*	Affiliations of the PI
Mission_group*	Data source name originally used in NASA/CDAWeb. Currently “SuperDARN” is set
Instrument_type*	Type of instrument generating the data set. Following CDAWeb naming convection, “Ground-Based HF-Radars” is set
Rules_of_use*	Rules of the road on using the data set. This consist of the official data policy of SuperDARN written in the PIs' agreement, and the special notes from the individual PI regarding the data use
Link_text*	Text describing on-line data available at PI or CoI web sites, to be combined with the following two attributes
Link_title*	Title of the PI or CoI websites
Http_link*	URL of the PI or CoI websites
Time_resolution*	Typical time resolution of the data set
Text_supplement	Some additional descriptions on the data set, currently left blank
Data_start_time	The start date and time of the data set
Data_end_time	The end date and time of the data set
RST_version	Version number of the Radar Software Toolkit (RST) which generated the data set
fitacf_version	Version number of the fitacf libraries used in generating the data set
rposlib_version	Version number of the rpos libraries used to calculate the position of radar pixels
calibration_history	History of the calibrations made for the data set
Known_problems	Known problems regarding the data set, such as data glitches and gaps
radar_position	Position in the geographical coordinates of the radar site
operation_start	The start date of radar operation
operation_end	The termination date of radar operation. This is left blank if the radar is currently in operation

* ISTP/IACG global attributes (http://spdf.gsfc.nasa.gov/istp_guide/gattributes.html)

Table 2 lists the data variables stored in the fitacf CDF files. In addition to the primary observables of SuperDARN radar such as the backscatter power (pwr), line-of-sight Doppler velocity (vlos), and spectral width (spec_width), a set of the important parameters stored in fitacf data files are copied to CDF files. Pwr_err, vlos_err, and spec_width_err are errors of pwr, vlos, and spec_width, respectively, deduced through fitacf fitting. Cpid, lagfr, smsep, and nrang_max can be referred to in identifying the radar operation mode under which data were obtained.

Table 2 Data variables in common time fitacf CDF

Variable name	Description
rgate_no	Range gate number
position_tbl	Table of positions (in geographical latitude and longitude) of four corners of each radar pixel
Epoch	The start time (in the CDF_EPOCH format) of observation of each beam
cpid	Control Program ID representing observation mode of a radar
int_time	Integration time in sec for each beam measurement
azim_no	Azimuth number of beam
pwr	Backscatter power in dB
pwr_err	Error of backscatter power obtained through fitacf fitting
spec_width	Spectral width of radar echo in $m \cdot s^{-1}$
spec_width_err	Error of spectral width obtained through fitacf fitting
vlos	Light-of-sight Doppler velocity in $m \cdot s^{-1}$
vlos_err	Error of light-of-sight Doppler velocity obtained through fitacf fitting
elev_angle	Elevation angle of radar echo (obtained when the interferometer is used)
elev_angle_err	Error of elevation angle
phi0	phi-zero angle representing the phase difference between the main antenna array and interferometer
phi0_err	Error of phi0
echo_flag	Echo flag (1: ionospheric echo, 0: ground scatter) based on the empirical criteria
quality_flag_info	Data quality information for each radar pixel given by ON/OFF of each bit of a 1-byte integer. 1st bit of the integer ON: echo power < 3 dB 2nd bit ON: spec_width > 100 $m \cdot s^{-1}$ (the other bits are reserved for future use)
quality_flag	Data quality as the number of ON bits of the quality flag info. Thus 0 is best and larger values mean worse quality
scanstartflag	Set to be 1 if the current beam is the start of a new 2-dimensinal scan, otherwise set to be 0
lagfr	Lag time in microsecond of the first range
smsep	Sampling separation in microsecond between neighboring range gates
nrang_max	Maximum number of range gate for the current beam
tfreq	Transmit frequency in kHz
noise	Noise level in dB
num_ave	How many times pulse sequences are integrated to get one beam data
txpl	Temporal length of a transmitted pulse in microsecond

We added a data variable "position_tbl" to CDF files so that users can refer to a table for the position (in geographical latitude and longitude) of each radar pixel for a given range gate number and azimuthal direction of the beam. With this position table, users can plot observed parameters on a map using only the CDF file; otherwise, the Radar Software Toolkit (http://superdarn.jhuapl.edu/software/superdarn/rst/index.html) needs to be installed separately to calculate the position table. Quality_flag and quality_flag_info are to be used by users to check briefly the quality of data. So far we have adopted two very simple conditions (backscatter power < 3 dB, spectral width > 100 $m \cdot s^{-1}$) to give a quality_flag value, and its breakdown is given by quality_flag_info. The quality flag and the breakdown are given for each radar pixel and each time frame. It should be noted that they are somewhat common but too simplified criteria and that satisfying both criteria does not immediately mean invalidity of data. If the quality flag is non-zero, users should analyze the data with caution. Because of the nature of remote sensing, we cannot provide any definitive flag to guarantee if a data value is valid at a glance. Thus, it is highly recommended to discuss the actual quality of data with the radar PIs.

Basically, fitacf data for one day and for a particular radar are converted to one CDF file. If one-day data contain measurements for different range gate numbers or beam numbers, each dataset for a particular range gate number and beam number is stored as a set of the 27 data variables listed in Table 2. For example, if the fitacf data for a day relate to two sets of range gate and beam numbers, two sets of 27 data variables are stored in a CDF file. Different data sets in a CDF file can be recognized by the suffix at the end of a data variable name. Specifically, data are stored in CDF files with a data variable name of "data variable name"_"suffix" (e.g., "vlos_0"). The notation of the suffix is given by Table 3.

Here we briefly describe the data flow for the fitacf CDF files, which is schematically illustrated in Figure 3. All radar data from the radar sites are first collected by Johns Hopkins University Applied Physics Laboratory (JHU/APL) and the collected data are subjected to initial checks. Subsequently, all radar data are transferred to the University of Saskatchewan and then stored on portable hard disk drives to be shipped abroad to each radar PI and SuperDARN scientists. This regular data shipment happens about four times a year and up-to-date data are delivered to the Solar-Terrestrial Environment Laboratory ("STE lab" in the schematic diagram), where the core team members of ERG-SC work on the CDF conversion. Upon arrival of new data, we extract only the common time data and fitacf CDF files containing such data are automatically generated. Only common time data are archived as CDF files because the SuperDARN Pis' agreement allows for a full open data policy only for these data and not for other particular mode data such as special time data and discretionary time data. The generated fitacf CDF files are readily available from the ERG-SC data repository at http://gemsissc.stelab.nagoya-u.ac.jp/data/ergsc/ground/radar/sd/fitacf/, as shown in Figure 4. Users can access the data files using Internet browsers or integrated data analysis software developed by ERG-SC, as described in the next section.

Table 3 Notation of the suffix of data variable names

Suffix	No. of range gate	No. of beam
0	75	16
1	110	16
2	70	16
3	80	16
4	100	16
5	75	22
6	100	22
7	75	24
8	100	24

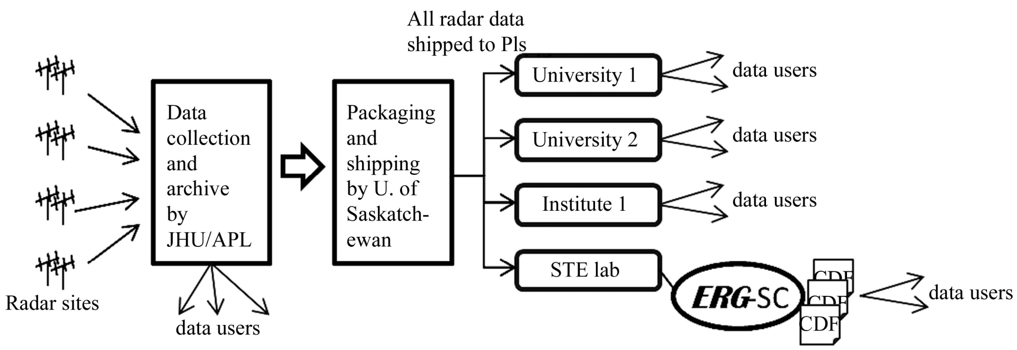

Figure 3 Schematic illustration of the data flow from the radar sites through the ERG-SC CDF repository.

3 Data analysis software based on TDAS

ERG-SC has been developing data analysis software in concert with the data repository of CDF files described in the previous section. The software is written in IDL, a commercial software suite for data manipulation and visualization(http://www.exelisvis.com/ProductsServices/IDL.aspx), and based on TDAS developed by and actually used for the THEMIS mission[13]. The ERG-SC software is currently provided as plug-in tools for TDAS. Advantages of using the TDAS platform is that user-friendly interfaces can be used to access CDF files as well as various kinds of data analysis/visualization tools included in TDAS. Currently, the "ERG-SC plug-in for TDAS" can handle the SuperDARN fitacf data in CDF as well as 210 magnetic meridian (210 MM) magnetometer chain data with 1-min time resolution[14], Iceland[15] and Showa, Antarctica magnetometer data[16], and the induction magnetometer data of STEL[17].

The top panel of Figure 5 is a screenshot showing an example of using the command line of the ERG-SC plug-in to load fitacf data in CDF. The command "timespan" is used to set the time range for which data are to be loaded. The subsequent "erg_load_sdfit" command downloads automatically fitacf CDF files from the ERG-SC data repository via the Internet, saves them on the user's computer,

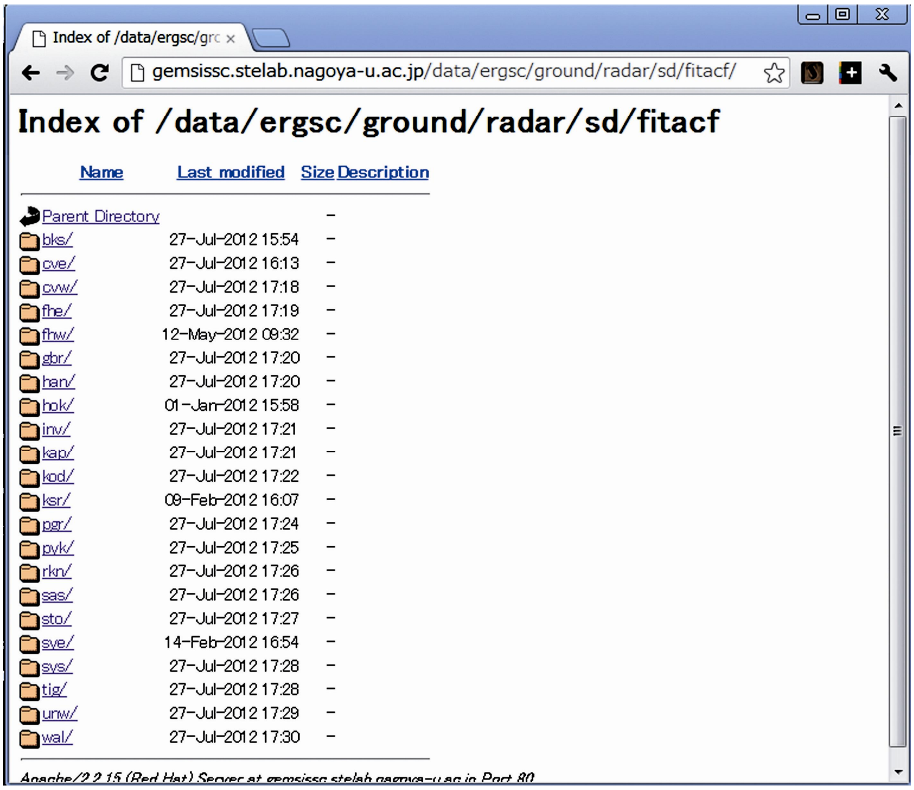

Figure 4 Appearance of the SuperDARN directories in the ERG-SC data repository viewed with an Internet browser.

and then reads the saved data files to load data in the IDL processing session as data structures with metadata.

One of the functions newly implemented by ERG-SC is to present the data policy to users upon loading data. Following the execution of the command erg_load_sdfit, the data policy is displayed in the command-line terminal automatically as seen in the top panel of Figure 5. This function is common to other ERG-SC data and should improve visibility of the important information described in the data policy statements regarding the data usage, limitations, and so on.

Finally, the bottom two panels are examples of SuperDARN data plots created by the ERG-SC plug-in. A range-time-intensity-type plot like that in the left panel can be drawn and even combined with other satellite/ground-based data easily to produce a stacked plot. Simple but powerful commands are also available to make a two-dimensional fan plot as shown in the right panel. Both the stacked plot and two-dimensional fan plot support multiple radar data. Thus, it is easy to load and draw multiple radar data in the same panel. The two-dimensional fan plot commands developed by ERG-SC basically work for the latitude-longitude grid platform defined by the map_set command. Therefore, any plot routines working on the map_set grid can be combined with the ERG-SC plug-in commands to create a map plot with multiple data. The TDAS supports an ascii dump of any loaded data using the command “tplot_ascii”. Accordingly, SuperDARN radar data can be output to an ascii file, which may be useful if users want to transfer the data to their own data analysis platform rather than using IDL.

The latest version of the ERG plug-in is freely available to all as a downloadable zip-archived file on the ERG-SC website at http://gemsissc.stelab.nagoya-u.ac.jp/erg_socware/bleeding_edge/. The stable version is to be included in the official TDAS libraries and will be released on the THEMIS website at http://themis.ssl.berkeley.edu/software.shtml.

4 Summary and future work

ERG-SC, in close collaboration with Japanese SD groups, developed the CDF, which is suitable for SuperDARN fitacf data. Through extensive collaborations with SuperDARN PI groups, ERG-SC has developed an open database of common time fitacf data where all data are archived as CDF files. We have also been developing an ERG-SC plug-in for TDAS to load fitacf data in CDF in the same manner as other satellite/ground data. The ERG-SC plug-in is a useful data analysis tool with which to load/analyze/visualize all kinds of data seamlessly.

As future work, we will continue to incorporate new kinds of data benefitting the realization of scientific goals of the ERG project into the CDF repository-TDAS scheme. In addition to the command-line tools, we have also been developing a graphical-user-interface-based data analysis tool for SuperDARN data as well as other ground-based data. This work is being carried out in close collaboration

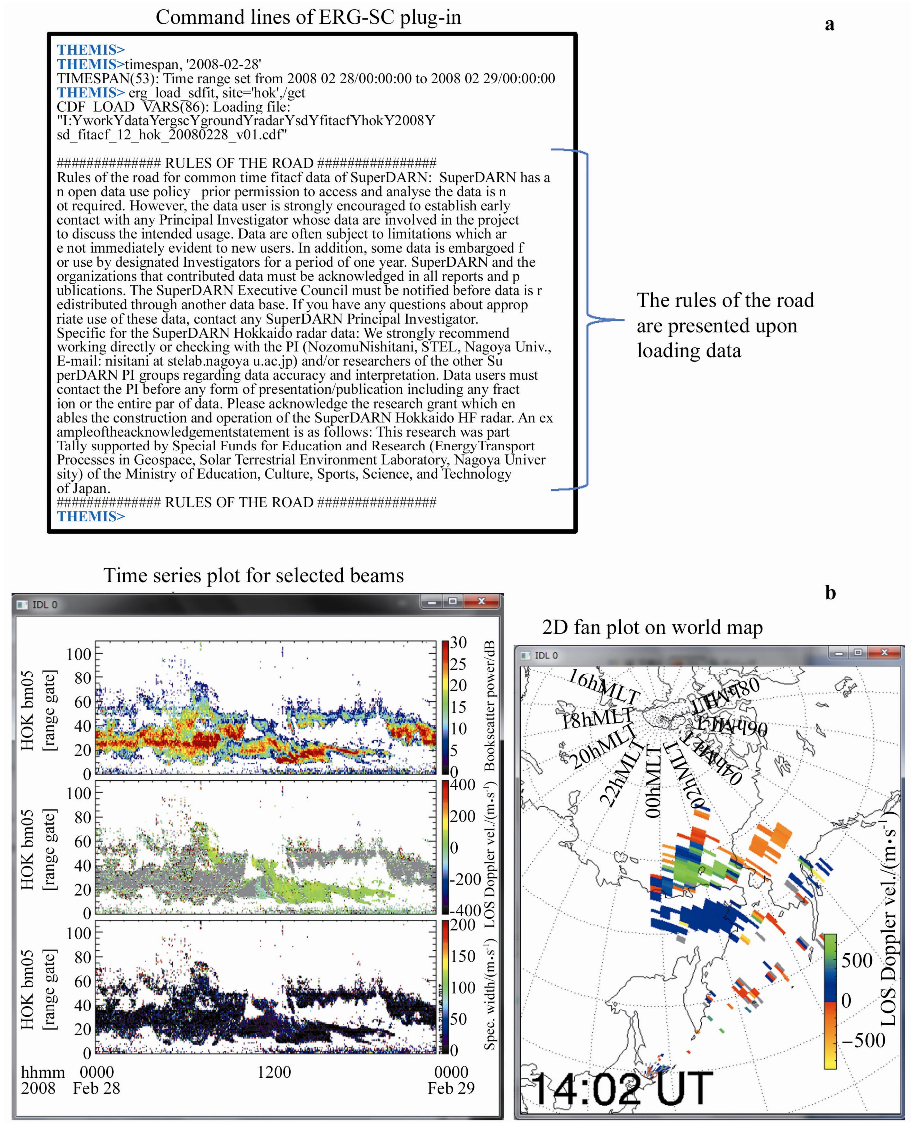

Figure 5 **a**, Example of the use of the command line of the ERG-SC plug-in to load SuperDARN data; **b**, Range-time-intensity-type plot and two-dimensional fan plot in the left and right panels, respectively, created by the ERG-SC plug-in.

with the Inter-university Upper atmosphere Global Observation NETwork (IUGONET) project[18], a Japanese metadata database project regarding ground-based observational data for the upper atmosphere (http://www.iugonet.org/). The CDF repository including fitacf CDF files and ERG-SC plug-in tools has already been opened to all users to use freely in their own research on not only the inner magnetosphere but also the outer magnetosphere/high latitude ionosphere. We welcome studies that can collaborate with the on-going project, such as the THEMIS and the Radiation Belt Storm Probes mission[19], in the pre-launch era of the ERG satellite.

Acknowledgments ERG-SC is grateful to SuperDARN PI groups for progressing collaborative work. We acknowledge the great cooperation provided by the TDAS development team in implementing our plug-in tools. We also thank all institutes and universities that have joined the ERG project for supporting ERG-SC.

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