WWW-based Visualization of the Real Time Run of a Space Weather Forecasting Model

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Abstract. As use of earth-orbiting space technology increases, so does the need to understand and forecast the space weather. The University of Alaska Fairbanks Eulerian Parallel Polar Ionosphere Model (UAF EPPIM) is a first principles three-dimensional time-dependant simulation, applied for real-time ionospheric forecasts. Its network-based continuous run uses on-line remote inputs, including current satellite data. Forecasted conditions are continuously visualized and disseminated via two mirrored WWW-sites www.arsc.edu/SpaceWeather and dac3.gi.alaska.edu/~sergei in various formats such as GIF-files, including their JavaScript animation; NCAR Graphics metafiles; and Vis5D databases. This paper describes practical approaches to issues such as synchronizing the model run to the real-time inputs and achieving the highest possible resolution on a variety of computational platforms. Experience running the model with network inputs continuously for nearly three years is presented and summarized. Examples of remote use of model forecasts are discussed together with new opportunities this real-time approach provides for the U.S. National Space Weather Program.

1 Introduction (Modeling Space Weather Phenomena)

The current 11-year solar activity cycle is expected to peak in 2000-2001. Combined with the dramatically increased dependence on space-based technologies, this upcoming solar maximum is attracting new attention to space weather phenomena. The U.S. National Space Weather Program has formulated a list of priorities in creating a capability to mitigate potential consequences of large-scale solar disturbances in Earth's close vicinity (www.ofcm.gov/nswp-ip/text/cover.htm). The need for operational real-time prognostic models with the capability to immediately disseminate forecasts is especially urgent. Simulations of the terrestrial ionosphere are an important part of this effort —particularly of the North Polar Region as satellite communication traffic is especially dense there. This paper summarizes experience creating the WWW-based real-time forecasting run of the University of Alaska Fairbanks Eulerian Parallel Polar Ionosphere Model (UAF EPPIM).

One of many peculiarities of the polar terrestrial ionosphere is a prominent advective motion in the horizontal direction at altitudes 150 *km* and up. The pattern of this motion is centered around the geomagnetic pole, though its mid-latitude edge regularly reaches as far as 50 degrees of geomagnetic latitude. The motion speed reaches 1 *km/sec* and up, which makes the process capable of significantly modifying all plasma parameters, including the electron density and its vertical profile. The plasma advection is governed by electromagnetic **E**x**B**-drift in the crossed Earth's magnetic field and the electric field of magnetospheric origin. While the Earth's main magnetic field can be assumed constant in time, the electric field is highly variable. It is controlled by a stream of energetic particles from the Sun, known as solar wind. Influence via the Interplanetary Magnetic Field (IMF), a field "frozen" into the moving stream, is the most pronounced. Significant variations of the IMF, including its drastic reversals on a scale of a few minutes, are a common occurrence [2].

Consequently, the advective motion pattern is in constant fluctuation. Combined with the considerable lifetime (several hours) of upper ionosphere plasma, this variability introduces a "memory" to the ionospheric system. Similarly to meteorological weather, the current space weather state depends not only on the immediate distribution of the forcing inputs, but also on their prior development in time. Such period-specific history is largely unique, and following its progression in the real-time simulation appears a feasible way to introduce prior influences into the forecast.

Another important characteristic of the terrestrial ionosphere (as well as the upper atmosphere in general) is that it responds quickly to changes in the forcing parameters. The significant variability of these parameters results in serious limitations in how far “weather-scale” ionospheric conditions can be predicted in advance. Currently, the practical limits of forward simulations cannot exceed one-two hours, the time scale at which the forcing parameters are predictable or measurable.

The EPPIM obtains forecasts of solar wind parameters via input from satellites placed at upstream positions between the Sun and the Earth. The probing satellite, ACE (Advanced Composition Explorer), is located near the gravity-free Lagrangian point (L1) at a distance of ~1.5 million kilometers (www.srl.caltech.edu/ACE/ASC). As the solar wind’s velocity ranges from 250 to 800 *km/sec*, while the data downlinking is practically instantaneous, the satellite provides real-time round-the-clock forecast of the solar wind parameters from 100 to 30 minutes in advance.

The L1 gravity-free location is uniquely advantageous for a long-term placement of the probing satellite. L1 can be orbited for years without depleting propellant supply. A global chain of several tracking stations is required for round-the-clock data downlinking from this type of trajectory. The real-time data online depository is located at the NOAA's Space Environment Center (ftp://solar.sec.noaa.gov/pub in Boulder, Colorado). This new practically non-interrupted availability of geophysical inputs makes the continuous real-time forecasting run of the EPPIM feasible.

2 The UAF EPPIM and its Real-Time Forecasting Applications

The University of Alaska Fairbanks Eulerian Parallel Polar Ionosphere Model is a first principles ionospheric model [3], which solves the equations of continuity, motion, and energy balance for seven ion species, electrons, and a few minor neutral atmosphere components important for the ionization balance. The model geographic domain covers a significant portion of the Northern Hemisphere (9,200x 11,000-*km* area), and extends vertically from 80 to 500 *km*. The model uses the Azimuthal Equidistant Projection to apply a Cartesian frame to the Earth's spherical geometry (Fig.1).

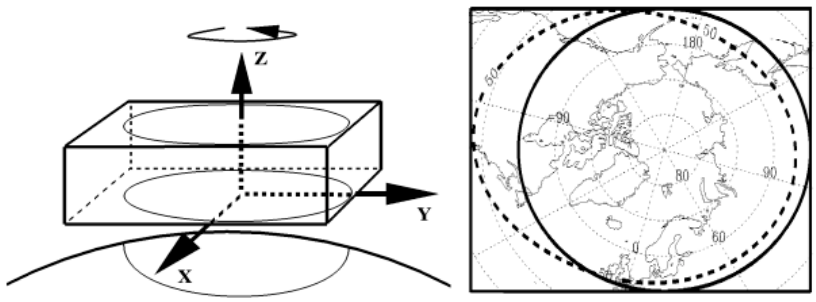

Fig. 1. Schematic representation of the UAF EPPIM domain. The Earth's spherical geometry (*left panel*) is mapped into a Cartesian frame using the Azimuthal Equidistant Projection (AEP), while the AEP metrics is used to compensate for resulted distortions. Right panel shows extent of the geographic coverage, the solid line circle represents 50°N geographic latitude, while the dashed circle corresponds to 50°N geomagnetic latitude

The UAF EPPIM flow chart at dac3.gi.alaska.edu/~sergei/Introduction.htm depicts the model structure. Its modularity allows variable approaches depending on input availability. For instance, the model interchangeably uses several electric field modules to generate the advective drift pattern. Among them is a statistical model [6], driven by the Interplanetary Magnetic Field parameters; or a combination of a statistical pattern and the current measurements from the polar chain of Doppler radars SuperDARN [5]; or, finally, a period-specific reconstruction of the electric field by Assimilative Mapping of Ionospheric Electrodynamics technique [4].

The UAF EPPIM code consists of ~25,000 Fortran lines structured into about a hundred subroutines. It supports the MPI-parallelization based on the domain decomposition as well as a single processor environment. Multiple porting and extensive scalar optimization developed the code's robust performance. This performance is well scalable both with an increase of processor power in a single CPU workstations and, in case of a MPP supercomputer environment, with the number of the assigned processors. One of the code environment variables is the model horizontal resolution, which sets the cell size from 220 *km* up to 10 *km* as a uniform mesh throughout the entire domain. Color Plate 1 demonstrates the resolution-related increase of the solution fidelity for the electron density. It shows consecutive magnifications of portions of the horizontal cross-section of the 3-D model domain, cut near the vicinity of the main maximum of the ionospheric layer *F2* at 290 *km* altitude. The left column represents the model sub-domain of ~2000x1500 *km* size and the right column shows ~1000x750 *km* area near the center, magnified. The otherwise geophysically identical runs differ only in horizontal resolution, namely ~220x220 *km*, ~ 55x55 *km*, and ~14x14 *km*, or factor of 16 for each transition.

It is evident from the picture that the relatively smooth solution obtained using a horizontal resolution of 220x220 *km* is replaced by an increasingly structured pattern as resolution increases. For applications related to satellite communications, it is important to simulate not only the electron density, but also electron density gradients. Gradient magnitudes are critically important for forecasting the growth rates of the ionospheric plasma instabilities, as these occurrences are known to degrade communication signal quality. Hence, high horizontal resolution can add significantly to ionospheric forecast comprehensiveness.

The EPPIM's time-splitting algorithm allows for varying the model's time resolution without jeopardizing its numerical stability. Using high time resolution (tens of seconds) provides the means to trace interesting short-lived developments, while low time resolution (tens of minutes) allows the same computational resources to cover extended periods. Frequently, a five minute time step is chosen for the EPPIM runs as a good compromise between reasonable time coverage and the computational effectiveness of the model. Time and space resolution can be adjusted to fit the performance of a given computational platform.

Table 1. Characteristics of several computational platforms and the UAF EPPIM horizontal resolutions, which they support for real-time simulations with 5 minutes time stepping

Platform, year	DEC Alpha 3000/300x, 1994	SGI O2, 1997	SGI Octane, 1999
SPECfp95	~2.6*	9.7	20.3
Horizontal resolution	80 x 80 km	50 x 50 km	30 x 30 km
Problem size	131 x 113 x 43	217 x 181 x 43	361 x 301 x 43
Memory needed	110 MB	290 MB	800 MB

* - Estimate from DEC Alpha 3000/300x value of benchmark SPECfp92 = 100

Generally, for a given computational platform the criterion of real-time compatibility of a time-dependent application can be formulated as follows: the elapsed time required for completion of the application time advance (the response time) should not exceed the time advance value (synchronization interval). Provided the EPPIM time advance is chosen at 5 minutes, it defines the highest possible resolution or the problem size for a given platform performance. (In all cases, the memory is assumed adjustable to accommodate any problem size.) Table 1 summarizes the achievable in real time horizontal resolutions of the EPPIM for several model ports.

For all combinations of platforms and resolutions in Table 1, the average wall-clock time to advance the model for one time step of 300 sec (5 minutes) was ~230-250 sec. Thus, the EPPIM code response time comprises ~80% of the real-time synchronization interval. By any means, this is a tight arrangement for a real-time run. To maintain synchronization it dictates a full dedication of system resources. The next question is whether a 20% of idling overhead is too wasteful. Even on a fully dedicated platform, a computation/idling ratio as 80/20% is justified. It accommodates possible fluctuations in computational time related to seasonal variability, quiet vs. disturbed geophysical conditions, etc. Next, allowing for a small idling time at the end of every time step is convenient for synchronization purposes. "Borrowing" this time for computations related to the next time step provides a flexibility to control dynamic shift between the model time and the current clock time during the run, as described below.

As shown in Table 1 and Color Plate 1, the UAF EPPIM can reach useful horizontal resolutions using workstation-class computational platform. High-end workstations support horizontal resolutions of 30x30 *km* and better. It is adequate for ionospheric density forecasting and providing reasonable density gradient estimates, an important goal for communication-related applications. Even though a real-time setting requires full platform resources for extended periods, as long as a dedicated workstation is significantly cheaper than a supercomputer, it is an economically feasible arrangement. Although dedication of expensive supercomputers is not unheard of in real-time meteorological forecasting, space weather programs are still in their infancy. It is important to bridge the gap between the real-time needs and current funding realities by developing scalable approaches, capable of effortless porting to available computational resources.

Finally, the real-time mode of the UAF EPPIM naturally creates a capability to continuously track the history of geophysical developments. To preserve model real-time performance for weeks- and longer runs, it is necessary to arrange a series of network exchanges to update the model inputs in a time-effective manner. The next chapter describes the networking solutions, which maximized the forecasting abilities of the EPPIM.

3 WWW-based Ionosphere Forecasting

As discussed above, the UAF EPPIM has a modular structure. Many modules exist in several interchangeable versions. The EPPIM supports simulations with real data but also can be switched for modules comprised of statistical description of various geophysical parameters. The statistical modules are driven by a limited number of geophysical indices. Among these indices are the solar activity index ($F_{10.7}$); the geomagnetic activity index (Kp); and the magnitude and orientation of the Interplanetary Magnetic Field (IMF). This combination is sufficient to invoke the statistical modules of the EPPIM to describe the current geophysical situation with a reasonable level of accuracy. This approach reflects the current stage of ionospheric modeling. Generally, an inclusion of real data for simulation is limited to post-analysis of specific space weather events. For the real-time prognostic run, when data availability is extremely limited, the EPPIM resorts to statistical descriptions driven by a combination of current or anticipated values of geophysical indices, available online for remote access.

The EPPIM network-based real-time run is hosted at the University of Alaska Fairbanks. The model time is dynamically shifted forward with respect to the current time and update of geophysical indices is arranged as a series of automatic network exchanges. The exchange frequency varies for various geophysical parameters. The slow varying solar activity index $F_{10.7}$ is assumed constant for the entire model day. During the run, its value is updated once a day from on-line depository at the Space Environment Center (SEC) ftp://solar.sec.noaa.gov/pub/latest/SRFF.txt in Boulder, Colorado. The synoptic nowcast of the geomagnetic activity index Kp is generated by the USAF Space Weather Squadron in Colorado Springs, Colorado and disseminated through the SEC depository ftp://solar.sec.noaa.gov/pub/latest/Mahr.txt. The file with the established Kp value for the previous hour is updated every hour at its 27th minute. Thus, the Kp index is updated in the model with a noticeable delay between one and two hours. This arrangement limits the precise timing for the Kp surges, but generally allows for trend tracing. In the future, we plan to use the Kp forecast for this input, which recently became available at the SEC.

The most variable parameter for updating during the real-time run is the Interplanetary Magnetic Field (IMF) magnitude and orientation, measured by the ACE satellite at 1.5 million kilometers from the Earth. It is available online also at the SEC depository ftp://solar.sec.noaa.gov/pub/lists/ace_mag_1m.txt. The file is updated every minute and includes the latest information on Earth-bound solar wind. Data is available in less than a few minutes after the instant the measurements are taken, which is a remarkable achievement of space technology. The EPPIM reading script applies the running averaging algorithm to cover the latest 10 minutes, which filters out the higher-frequency random component and leaves the IMF variation trends intact, from which statistically realistic ionospheric drift patterns can be reconstructed.

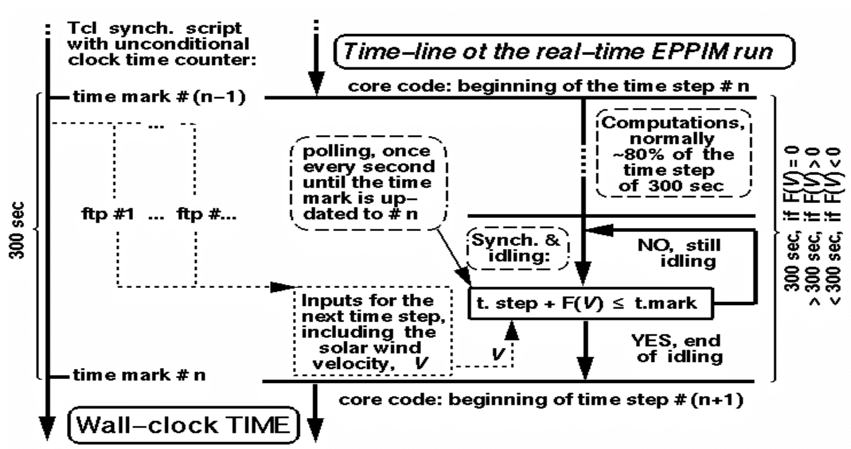

Fig. 2. Parallelization of the EPPIM UNIX processes during a real-time run. The Fortran computational part of the code upon completing each time advance checks the absolute timing marks from the Tcl script and makes a decision whether to continue idling or to proceed to the next time step. The decision depends upon many factors, including the current shift of model time vs. wall-clock time and the solar wind anticipated delay, expressed as *F(V)*

Due to the upstream position of the ACE satellite in the solar wind, it takes a certain amount of time for a sampled solar wind parcel to propagate to the Earth's vicinity from the measurement point. Since the information about incoming variations is available in some advance, the model time of the run is shifted forward to accommodate this advance. This shift facilitates the model's forecasting capability and it is essential to arrange its dynamic update during real-time runs of the EPPIM, which may extend for weeks. The advance time varies depending on the current solar wind velocity, while the distance to ACE can be assumed constant. Another file from the SEC depository is read to find the current velocity of the solar wind. Compared to the IMF, this is a slowly varying parameter. For the ACE location at L1 point, the advance time is in the range 30 to 100 minutes with an average value at about one hour. The dynamic adjustment of the model time shift with respect to the current clock time is schematically shown in Fig.2 as elimination—or increase—of idling time at the end of each time advance.

As follows from the discussion above, the real-time ionospheric model run requires a frequent repetition of many ftp-requests to maintain the inputs updated. This can severely degrade the code's performance if the transfers are invoked sequentially. A network transfer of a few kilobytes is a very fast process, but with several files the accumulated wait for connections, etc. can significantly increase the time required to gather necessary data. Consideration of the worst case scenario is the only feasible way to create a stable application with operational capabilities. During a continuous real-time run of the EPPIM it is necessary to perform about 2000 time advances weekly, which means roughly ~5000 ftp-exchanges. A practical approach to recover the code from the inevitable ftp failure is to impose a hard time limit for each ftp-attempt. If ftp-ing fails, the run continues using the input values from the previous time step. However, the percentage of misses can be unacceptably high if the time limit is too small. After a long period of fine-tuning, we allow several minutes for each ftp process to reduce the misses to a reasonable level of 5-10%.

Such generous allocation conflicts with our 80/20% ideal of computation to idling time ratio. Potentially spending several minutes per timestep waiting for a slow file transfer is an unacceptable waste. A simple solution is to use the natural parallelization available in a UNIX environment and execute all ftp requests as a separate and backgrounded processes of lower priority using `nice` utility (`>nice –2 "ftp-ing script"`). The `nice` priority level of 2 a good compromise and dramatically reduces the total idling time.

4 Visualization Solutions

The goal of running EPPIM in real-time forecasting mode is to disseminate space weather information as widely and rapidly as possible through its WWW-site. The site is designed to be useable both for fast reference to ionospheric conditions (pre-prepared 2-D "ionospheric maps"), and for research collaboration, such as during ionospheric measurement campaigns. These users, who can be called "high-end users", are interested in model outputs in formats suitable for real-time or near real-time downloading to remote powerful resources for in-depth interactive analysis.

Color Panel 2 shows the basic format adopted at the EPPIM Web-site for 2-D maps to demonstrate both the ionospheric developments and variation of input parameters. The visualization is performed at the end of each model time step by the NCAR Graphics package. The resulting NCAR Graphics metafile is a convenient cross-platform vector format, supporting both direct viewing and/or batch-mode rasterization into widespread formats such as GIF. The adopted "geographic latitude vs. local time" frame allows for permanent positioning of the local noon (upper side of the plot), midnight (lower side), and, correspondingly, morning (right) and evening (left), independent of Earth's rotation. The input values are also placed on the map, either as textual information (time and date stamp, solar activity, etc.) or in graphical representation (Kp, the IMF magnitude and orientation). Several operations are performed to simplify the picture (generalizing contouring) and its interpretation (adoption of discreet color code, geographic coordinate mesh). This approach enables a user to attribute certain geographic locations with the current values of ionospheric parameters and to evaluate the regional ionospheric conditions in general.

The EPPIM WWW-site is hosted on a server, which is not involved in computations. This separation facilitates handling of the WWW-requests much faster than from the dedicated platform under heavy computational load. Additionally, under this mini-cluster arrangement the WWW-handling does not interfere with computations, making the run timing more predictable. The clustering allows the computational processor to assign certain visualization tasks to the WWW-server. When the NCAR Graphics metafile is ready, the clustering arrangement uses an *ssh*–connection to the WWW-server to trigger the pull of metafile from the computational platform and rasterize it subsequently. After the copying is completed, the computational processor continues with the next modeling task, while the WWW-server uses a batch mode of the NCAR Graphics utility `ctrans` and software rendering to rasterize the metafile. The limited number of colors facilitates an effective transformation to the economical 8-bit GIF format. Two images are prepared at each time step, one at resolution 511x431 with a general view of the ionospheric map and the geophysical inputs, and another with a magnified map (431x431). The metafile itself is made directly accessible to WWW-users. It can be ftp-ed for local viewing by the native NCAR Graphics viewer `idt` with non-lossy zooming capabilities, including an option of animating a magnified area of interest if a sequence of metafiles is downloaded and appended with NCAR Graphics utilities.

For the horizontal resolution of the current run at 80x80-*km*, the metafile size is in the range of 60-80 kB and the two GIF-views require 20-25 kB each, depending on image complexity. Thus, the model generates about 30MB of graphical information daily. This imposes the need to arrange an expiration of the outdated information at the WWW-site to maintain its size within reasonable limits. Currently, the site stores ionospheric maps covering the last 24 hours. This collection of single frames creates opportunities for the animation of ionospheric developments. However, for this setting deciding what method of animation to use is not trivial. Formats like QuickTime or MPEG exploit interframe coherence and can noticeably compress the resulting animation. The price paid is a heavy CPU load at the WWW-server. Since the ionospheric map is permanently updated, the life span of a pre-prepared animated sequence will be just 5 minutes before it is outdated. Thus, it is not practical to constantly modify these movies, as this would overload the WWW-server's processor.

In addition to the obvious solution of only generating animation on demand at the WWW-server, the task of developing animation can also be delegated to the viewer's workstations. The site provides a JavaScript-based animator to download the desired number of GIF frames and combine them into an animated sequence on the user's screen. The script supports playback both in forward and in reverse direction with variable speed, frame by frame advance, and pause. It requires a transfer of ~0.5, ~3.0, and ~8 MB of data and 16, 32, and 64 MB of free RAM to animate 3, 9, and 24 hours of the ionospheric developments represented by 36, 108, and 288 frames respectively. Some intermediate combinations with skipping of every second or third frame are also supported, which allow covering the same period of modeled time with a smaller data transfer. A strong side of this approach is an immediate response to the WWW-request and the animation "previewing" while downloading. By contrast, a generation of compressed movie on demand requires several minutes only to produce it without counting time for downloading. Admittedly, the adopted approach assumes that the client workstations are powerful enough to handle the animation load, which is generally true for the site's target "high-end users". Several representative pre-compressed animations in conventional formats are available at the site for re-playing.

Still, animated or steady ionospheric maps are just 2-D cross-sections of the 3-D multi-variable simulation domain. Volume rendering is still a challenging task for remote visualization. We approach its solution by using Vis5D format for the ionospheric datasets. The volume rendering package Vis5D [1], freely available for downloading from its home site (www.ssec.wisc.edu/~billh/vis5d.html), is a powerful graphical tool for exploration of complex 3-D time-dependent datasets. It is compatible with a variety of UNIX platforms and has been ported to Linux, WindowsNT, and OS/2 environments. Cross-platform capabilities of Vis5D allow it to function as a WWW-browser plug-in. To facilitate this capability during the real-time run, at every time step the EPPIM outputs a 3-D distribution of the essential ionospheric parameters from the entire modeling domain or from its representative part into a Vis5D database. The Vis5D format applies powerful data compression up to one byte per node per variable, reducing the overall size of the data file to a manageable level. For the current real-time run dimensions of the EPPIM grid (113x135x43), the size of volumetric data for one scalar variable is reduced by this compression to 0.65 MB. Output of the every second node in the representative altitude sub-range of 200-400 km reduces this number to ~0.1MB. The EPPIM real-time users can download these files —either with full or with reduced resolution— and open them locally with the Vis5D viewer. Additionally, a simple script placed in a *crontab* shell allows for automatically appending the Vis5D database by ftp-ing the current data every 5 minutes. Thus, the site's "high-end users" can acquire both animation and volume-rendering capability for their ionospheric data analysis (Color Plate 3).

4 Conclusions and Future Work

This paper presented a case study of computational, networking, and visualization arrangements to maintain a synchronized real-time run of the ionospheric model on a practically permanent basis. This study directly relates to space weather, however its findings are useful for development of network-based applications in various fields. From a computer visualization standpoint, an aggressive use of such elements as run-time visualization and animation, networking, clustering, and computational steering made the scope of this study more universal than geophysical modeling.

Our immediate future plans include an upgrade of the run's computational platform with an order-of-magnitude more powerful workstation SGI Octane, which was provided by the ARSC for this goal. It will allow us to dramatically increase the run horizontal resolution to a 30x30-*km* cell and to consider more geophysical parameters, such as electron density gradients and growth rates of plasma instabilities. New computational and graphical power will also allow us to proceed to an interactive 3-D representation of the ionospheric fields, both locally and remotely using Java- and JavaScript-based approaches.

The availability of a second computational platform for dedicated real-time runs will help us to utilize alternative approaches to the polar ionosphere nowcasting, such as using the direct measurements of the plasma motion from the SuperDARN Doppler radar network [5]. Additionally to a run with IMF-driven statistical advection patterns, it opens numerous opportunities for comparisons of modeling results between different runs, different empirical and database-type ionospheric models, and with the data from the global ionosonde network now available on-line. It is important to note that space weather real-time capabilities are relatively recent developments with a long-term potential. The space weather research community expects a continuation of monitoring at the solar wind upstream locations. The next generation satellite design (2003) includes a solar sail to shift the equilibrium point further sunward to increase the time advance of the measurements and, consequently, the forecasts.

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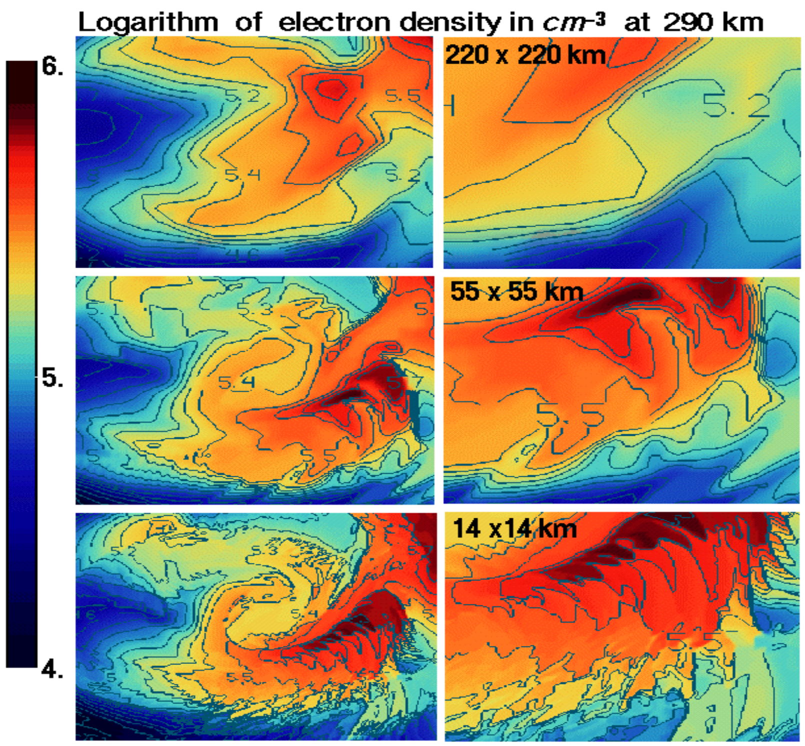
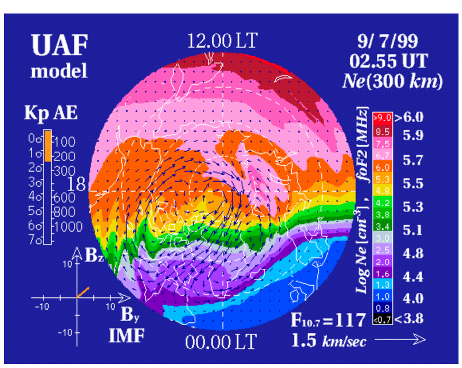
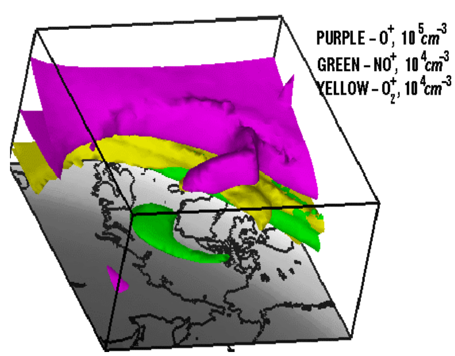


Color Plate 1. Electron density at 290 km, simulated with EPPIM at specified resolutions. Isocontours are drawn at every 0.1 in the log-scale, correspondingly to a factor 1.26 for density



Color Plate 2. Example of ionospheric map from the EPPIM WWW-site dac3.gi.alaska.edu/~sergei



Color Plate 3. Vis5D representation of the EPPIM volumetric output