Improved polar HF propagation using nowcast and forecast space weather parameters

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Abstract. The short-term variable impact of the Sun's photons, solar wind particles, or magnetic field upon the Earth, i.e., space weather, is the major cause of high-latitude ionospheric perturbations. It particularly affects HF radio signals reflected from the ionosphere by polar-transiting aircraft. To improve polar HF radio propagation capabilities, we present work in progress on an innovative concept using space physics models that are now operationally mature and that are linked to well-known ray-trace computer code. Supplemented with existing, measured electron densities in local areas, the end result will provide substantially improved polar HF aircraft radio communication. We are linking the SOLAR2000 model's nowcast and 72-hour forecast of solar irradiances and proxies with the GAIM ionosphere model. The 4-D electron density profiles that are output from GAIM are additionally improved by future input of the nowcast/forecast plasma drift velocities from the DICM electric circuit model. The electron densities will be used by the ICEPAC ray-trace model within the Dynacast system to provide a regional polar HF suite of frequencies that are ranked for each waypoint and from every possible service provider. Dynacast electron density measurements may also be incorporated to improve the local HF propagation capability. We are developing a platform to link all models and data via automated processes on several servers. The resultant suite of frequencies that we are developing will be provided to global messaging systems such as GLOBALink and the HF Data Link system for use by commercial aviation operating in the polar region. The system, as it evolves, will be robust and redundant, using a distributed-platform architecture. This system concept represents one of the first major implementations of space weather operations for use in commercial aviation and we describe our initial work.

1 Background

1.1 Space weather, polar HF interference, and GPS signal error

The ionosphere, under quiet conditions, is created and affected by incident solar extreme ultraviolet (EUV) radiation and the processes of ion and electron loss due to neutral constituent chemical reactions, ionospheric electrodynamics, and ion drag from thermospheric wind. Under disturbed conditions, especially during geomagnetic storms and substorms, enhanced electromagnetic activities and incident charged particle fluxes significantly change ionospheric electron density distributions. This is especially true in the polar region which is nearly always moderately disturbed except during northward interplanetary magnetic field (IMF) intervals and in the auroral zone which is disturbed during local magnetic nighttime substorms. This short-term variable impact of the Sun's photons (irradiance) or particles (solar wind) upon the Earth is known as space weather and is the major cause of high-latitude ionospheric perturbations. It affects the ability to reflect HF radio signals from the ionosphere by polar-transiting aircraft. In low- and mid-latitudes, these same sources can create rapid changes in the ionospheric total electron content (TEC), adversely affecting the timing and/or availability of GPS signals that propagate through the ionosphere. These conditions reduce the accuracy of single-frequency GPS receivers used by ground and air missions. Until now, our limited nowcast/forecast knowledge of these space weather effects on polar HF communications and low-, mid-latitude GPS signals has hampered our ability to fully utilize our technological systems.

1.2 Polar air routes example

Cooperation between Canadian, Russian, and U.S. aviation authorities has led to the establishment of four civilian polar air routes between 79° and 89° north latitude. Military users have additional but similar polar routes. These routes between paired cities in North America and Asia significantly reduce flight times on east to west flight segments. Polar routes avoid the strong North Pacific jet stream headwinds. Civilian polar routes (figure 1) include Chicago to New Delhi, New York to Hong Kong, San Francisco to Beijing, and Tokyo to Paris. Polar routes are the shortest travel distance from the continental U.S. to central Asia and can be used in search and rescue operations, logistical support missions, as well as during emergency landings. Polar routes save travel time and fuel, resulting in lower maintenance and operations costs with fewer takeoffs and landings.

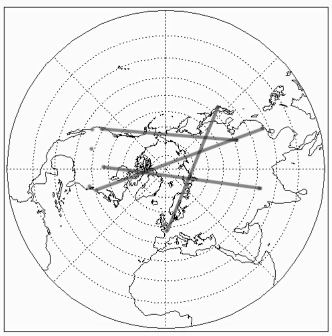

Figure 1. Representative polar routes between paired cities in the northern hemisphere.

Civilian aircraft entering, traversing, and exiting U.S. airspace have a regulatory requirement to maintain contact with air traffic control, but the use of Very High Frequency (VHF) line-of-sight communications to ground stations can leave gaps in excess of six hours on polar routes. Aircraft equipped with satellite communications can experience communication gaps of over two hours. In the political environment with civilian aircraft threats, there is a security requirement for radio link capabilities at all points along a flight path. For military missions, the option of a radio link is required and this makes a redundant operational communication system highly useful. Therefore, there is strong economic, time, and security rationale for maintaining radio links with all polar-transiting aircraft and HF radio fills gaps in this need.

HF 3 – 30 MHz radio signals are capable of long-distance, over-the-horizon propagation as a result of signal bounce off ionospheric layers. The one- or multi-hop calculation of a signal bounce off the ionospheric E and F2-regions can be performed with ray-trace algorithms. Since the radio signal is reflecting off ionized layers, the ability to reflect is dependent upon the space-weather modulated electron density within the various layers of the ionosphere. It is possible to specify the characteristics of this reflectance layer and we present our first steps in developing this operational capability.

1.3 State of space weather operations

The variable solar photon and charged particle fluxes that interact with the Earth's atmosphere, ionosphere, or magnetosphere are specified in near real-time from ground and space-based measurements and from models that use flux surrogates. In the early 1990's the OpSEND system was developed as the first breakthrough system of this type. For example, OpSEND provides nowcast HF communication and GPS single-frequency error maps for military users. It is operationally implemented at 55th Space Weather Squadron with a web interface for DoD users. It is based on the PRIZM ionospheric model and driven by legacy nowcast solar and geomagnetic inputs (F10.7 and ap).

The system we are developing is a major advance beyond OpSEND. We are developing solar and geomagnetic specification based on an existing and continually-improving 72-hour solar energy and solar particle forecast. In this early stage, we are working to couple these operationally forecast values with the ICEPAC ray-trace model running with the Dynacast system for providing a suite of frequencies. In a next phase, we will provide inputs to the Global Assimilation of Ionospheric Measurements (GAIM) ionospheric model that uses data assimilation and will then run in forecast mode. In the future, when GAIM is operational, it will likely include high time resolution TEC data from platforms like SBIRS Low. In this next stage, however, we are developing that foundation by including electric field perturbations to the GAIM ionosphere via the DMSP-based Ionospheric Convection Model (DICM) model. The overarching goal of our system is to provide operational access

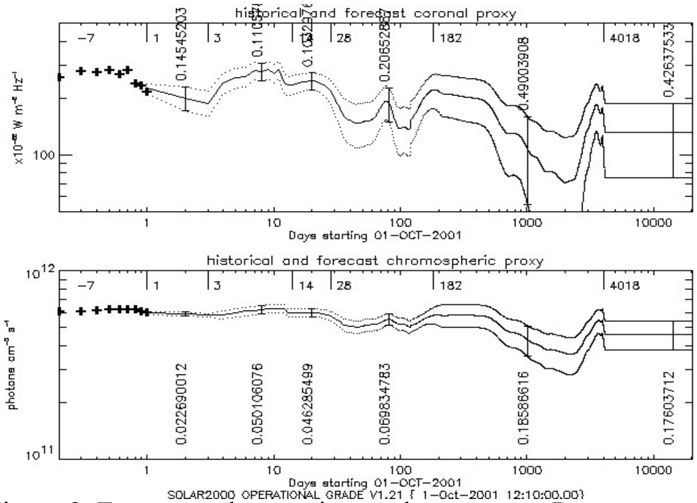

Figure 2. Forecast solar proxies used to generate Rsn, E10.7, and I(λ) in the operational SOLAR2000 model. The uncertainty grows larger through time.

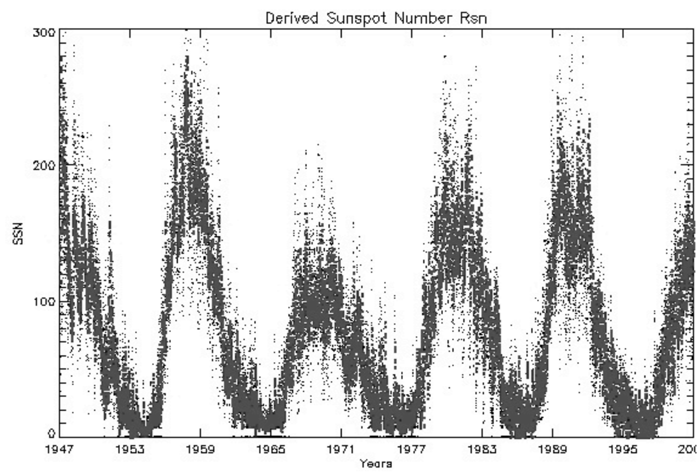

Figure 3. Rz and Rsn plotted for solar cycles 18 through 23. The Rz values are light and Rsn are dark.

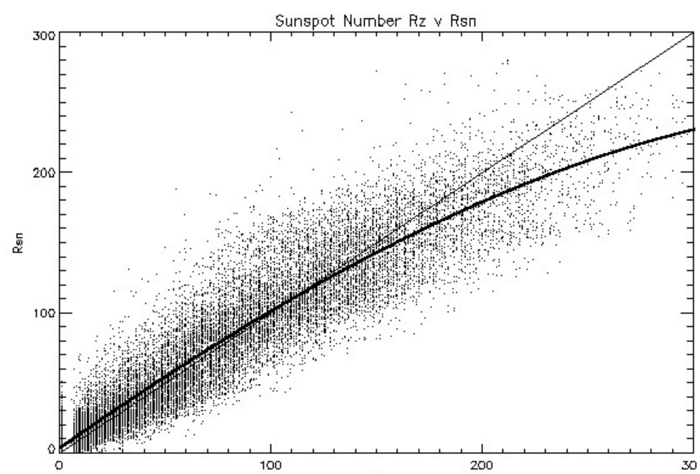

Figure 4. Scatter plot of Rz and Rsn. A straight line demonstrates a perfect fit and a curved line indicates the actual fit. Rsn produces less energy for photoionization at solar maximum and also does not reach 0.0 at minimum.

by commercial and military aviation to substantial improvements for HF radio propagation links via coupled automated servers and messaging systems.

The models that enable this operational system are derived from space physics research and now exist for specifying solar irradiances, the global electric field and plasma (electron) drift velocities, ionospheric electron density profiles, and ray-tracing of radio signals that propagate between two points. Advances during the past two decades have brought these models to either operational or near-operational capability. For example, the forecast solar proxies (figure 2) that produce irradiances, I(λ,t) and the E10.7 proxy used by ionospheric models as well as the sunspot number, Rz, used by ray-trace models, are now provided operationally by the SOLAR2000 model [Tobiska, *et al.,* 2000].

A new solar parameter is presented here and is called the derived Sunspot number, Rsn. It is particularly interesting in that it captures the best estimate of the energy actually available for photoionization at the top of the atmosphere, i.e., energy that is relevant to the formation of the ionosphere. This new proxy is reported in units of the traditional Wolf Sunspot number (Rz). Rsn is calculated from a 3rd degree polynomial fit between E10.7 and the Sunspot number for 5 historical solar cycles. A comparison of Rsn and Rz can be seen in figures 3 and 4. Figure 3 shows the 5 solar cycles of Rz (light data points) and Rsn (dark data points) and figure 4 shows a scatter plot of Rz versus Rsn. The Rsn values have a lower magnitude than Rz at solar maximum and also do not reach the value of 0.0 at solar minimum. The implication is that there is less solar EUV energy input into the upper atmosphere than would be suggested by the traditional Sunspot number and, during solar minimum, there is always some minimum level of energy input into the upper atmosphere.

The models we are currently working with include the GAIM model (figure 5) which will use these solar irradiance and geomagnetic inputs to produce electron/ion density profiles for input into ray-tracing algorithms. The DICM model (figure 6) [Papitashvili, *et al.,* 1998, 1999, 2002] now produces nowcast and forecast plasma drift velocities based on the perturbed electric field and will be incorporated in GAIM in a next stage of our work. The ICEPAC model [ICEPAC Technical Manual, ICEPAC User's Manual] currently inputs the solar, geomagnetic, and electron density data, uses ray-tracing algorithms, and provides the window of usable HF radio signals that are possible for propagation between two points in a changing ionosphere. We are at the initial stage of making an operational version of ICEPAC. The Dynacast® forecasting engine [Goodman *et al.,* 1995] optionally uses VOACAP and ICEPAC models as subroutines and has all of the features of both models. In addition, Dynacast provides a proprietary algorithm called Dynacap® that facilitates model update using external data and enables areas of coverage as well as isolated aircraft tracks to be treated. All these models currently exist, have an operational or near-operational capability, and we are at the initial stages of linking them.

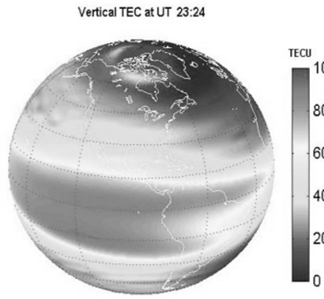

Figure 5. GAIM model representation of global ionospheric densities and TEC on a latitude/longitude grid and at a specified time.

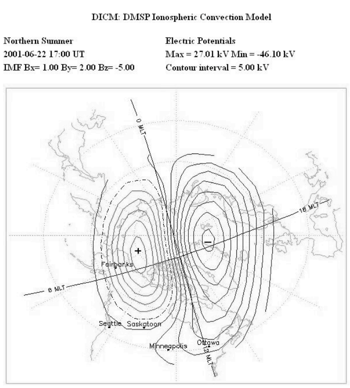

Figure 6. The DICM model output. The contoured electric fields are turned into ion drift velocities.

2 Operational system solution

2.1 Concept-of-operations

The work we have started is based on a concept-of-operations. The flow of operations is summarized in figure 7. SpaceWx is now operationally providing, via asynchronous server connections, the nowcast/forecast SOLAR2000 solar irradiance parameters (Rsn, I(λ,t), and E10.7) and the NOAA/SEC mirrored geomagnetic indices (Kp and ap) on an hourly cadence with 3-hour time centers. Appendix A shows the bulletin that provides all but the I(λ,t) values. These are the parameters that will next be used by ICEPAC within the Dynacast system and by GAIM. The ray-trace model, using only the solar irradiance (Rsn) and geomagnetic (Kp) indices, will provide a baseline frequency of transmission (FOT) for polar quiet ionospheric conditions. This configuration will be a background operational mode using a climatological model that operates with the best estimates of the current conditions.

Here, the FOT is used as a short-hand descriptor. It is different from the final operational product that will be a specification of the best frequency suite, ranked, for each way-point and from every possible service provider (ground station). The FOT (~85% MUF) represents the optimum working frequency for a specified link in a climatological model with classical layering. In this context, it is a good barometer for specifying the most reliable frequencies from amongst those that are available. However, operationally, the statistical FOT is not used. Instead, the instantaneous maximum operating frequencies (MOFs), with their distributions for each reflecting layer and the signal-to-noise ratio (SNR) which has a temporal distribution as a function of frequency, are used.

An advanced operational mode we are developing will use GAIM incorporating I(λ,t), E10.7, and ap inputs, modified with near real-time global JPL (and/or SBIRS Low) TEC. We will place the nowcast/forecast DICM global electric field inputs into GAIM with the possibility of including Dynacast measured electron densities. The interim product will be a 4-D electron density profile (latitude, longitude, altitude, and time) representing the best estimate of a moderately disturbed ionosphere at the current epoch. The GAIM electron density profiles will then be input into ICEPAC within Dynacast to produce the MOFs.

In the initial and advanced operational modes, ICEPAC within the Dynacast engine will operate in an automated batch mode and the outputs will provide a dynamic and updated knowledge of HF capability. The output ranked list of suitable frequency bands will be provided directly to air operation centers, aircraft, and radio service providers.

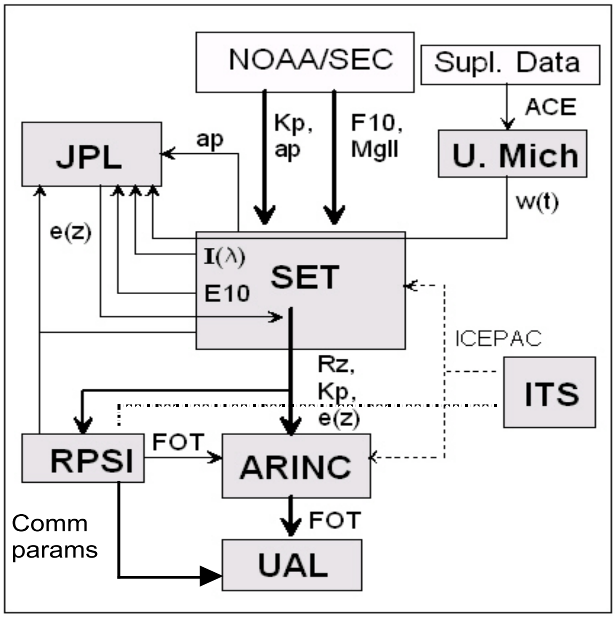

Figure 7. Top level flow chart of data/model input and output from raw space weather data to the best, ranked frequency suite supplied to an aircraft.

The diverse cadences of the model runs are related to the time constants and data availability in the physical processes they are representing. For example, the solar irradiance and geomagnetic indices of I(λ,t), E10.7, Rz, ap, and Kp are generated operationally on 3-hour time centers, updated on hourly time intervals, and forecast 72-hours into the future and beyond. The plasma drift velocity, w(t), from DICM will be updated every 10 minutes and GAIM electron density profiles, $N_e(x,y,z,t)$, will be updated hourly for initial global operations with a coarse latitude/longitude grid and every 10 minutes for advanced operations providing higher spatial/time resolution of the polar region. Dynacast measured electron densities are provided on a cadence of every 5 minutes.

The linkages of these solar, electric circuit, ionosphere, ray-trace model and data, along with the operational output of the latter, are the glue of this system. The entire system is modularized and the computer code is running or will run separately, operationally, and continuously. Redundancy exists through dispersed geographic locations, separated machines and operating systems, and independent data/model inputs and outputs. We are presently developing a database system to enable the computer programs to exchange ASCII files asynchronously so as to ensure inter-platform robustness. This architecture maximizes the ability to provide continuous services in a climate of potential external disruptions.

An example of the initial start of this capability is the Space Environment Technologies/SpaceWx operational system. Figure 8 demonstrates the 3-day forecast solar irradiance E10.7 proxy shown with the previous two solar rotations (54 days) (top panel) and against historical values (bottom panel). Figure 9 shows the continuously updating solar cycle trend of the solar data. The 3-hourly nowcast and forecast solar irradiance and geomagnetic parameters are provided through the bulletin previously mentioned. The 3hE, 3ha, 1sE, and 1sa columns are the inputs required by the ionospheric model. The 3hR, 3hk, 1sR, and 1sk columns are the inputs required by the ray-trace model. The nowcast/forecast products that are available from NOAA/SEC, such as the Kp and ap geomagnetic indices, will continue to be mirrored by SpaceWx through the on-going CRADA agreement [CRADA, 2000]. As a side-note, the nowcast/forecast ap index is being significantly improved through a separate SpaceWx

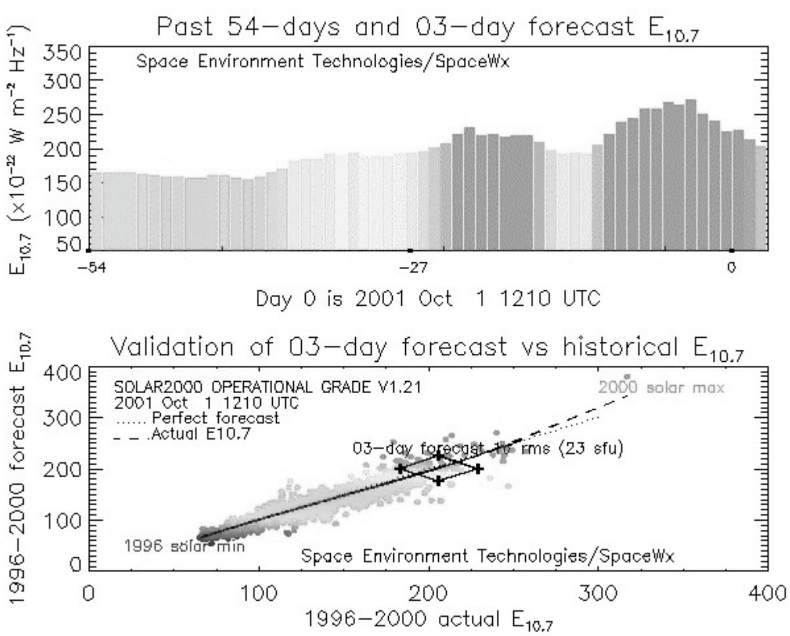

Figure 8. The 3-day forecast solar irradiance proxy E10.7 shown with the previous two solar rotations (54 days) (top panel) and against historical values (bottom panel).

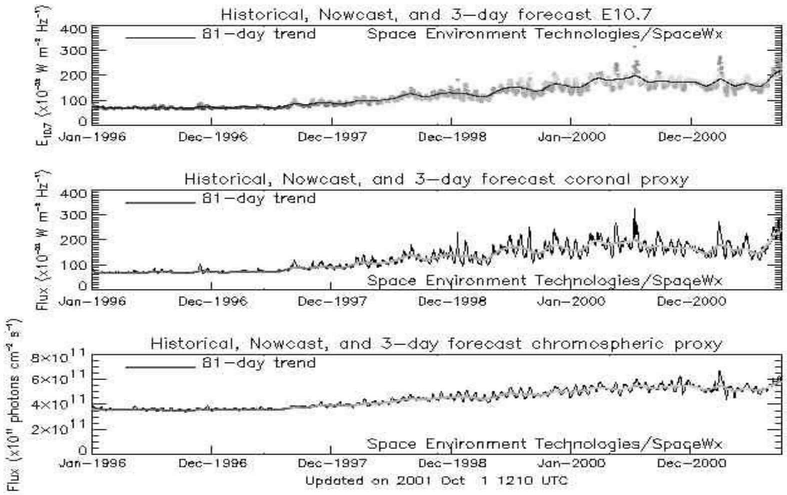

Figure 9. The solar cycle 23 historical trend of the E10.7 proxy and the coronal as well as chromospheric indices used to generate the proxies.

project in collaboration with SEC. For operational considerations, the nowcast/forecast indices best-estimate and the 1-sigma uncertainty are both provided.

2.2 Summary of operation phases

Our operational system is being implemented in three phases. In the first phase, a quiet global ionosphere HF link capability is being developed to prove the overall technical feasibility and to define the interface requirements for an operational ICEPAC as part of Dynacast. We will finish this phase by testing the solar/geomagnetic nowcast and forecast inputs (Rsn, Kp) to ICEPAC and validate the FOT outputs. The operational components now exist in this phase and their linkage is the next immediate step.

In the second phase, a moderately-disturbed global ionosphere HF link capability will be implemented by using solar/geomagnetic nowcast and forecast inputs in GAIM. In this phase, the electron density profiles will be implemented in ICEPAC, will be tested and validated as an end-to-end operational system.

In the third phase, a moderately-disturbed regional ionosphere HF link capability will be implemented and tested using the electric circuit DICM model plasma drift velocity outputs that will be transferred into GAIM. Validation of the revised GAIM output using w(t) will be conducted to verify regionally increased spatial resolution. The TEC will also be incorporated into GAIM by this phase to improve estimates of mid-, low-latitude GPS signal availability. Finally, the ICEPAC output from Dynacast will be validated for HF regional link improvements and will be tested as well as validated as an end-to-end operational system.

3 Summary

We are at the initial stage in the development of an integrated, robust space weather operational system that will provide new polar HF propagation capabilities for civilian aircraft and will provide a redundant system for military missions. It also will provide the basis for more accurate GPS single-frequency location knowledge in low-, mid-latitudes.

The system links aeronautical with space systems via coupled models and will provide cost reductions and improved safety for commercial and civil aircraft operations. For military users, the system will support improved aircraft deployment and logistics capability. It will also support force projection using rapid ingress which requires improved air communication links. New classes of missions are enabled by this system, particularly those that require either shorter travel times from the continental U.S. to other hemisphere locations or higher accuracy single frequency GPS use. This system, when fully operational, will provide substantial support for expanded flight regimes in polar and low, mid-latitudes and will exploit the phenomenology of space weather as observed from space platforms. It will incorporate continual improvement in knowledge from space physics models, establish a new but redundant communications system, incorporate data fusion, and even provide the technical knowledge to deny situational awareness to other parties. For these reasons, this operational system for improving polar HF radio and GPS accuracy, using space weather real-time knowledge, is a breakthrough capability.

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Appendix A. HF nowcast/forecast data

```
:Product: HF Input Data                          hfi.txt (Rev. A)
:Issued:   1-Oct-2001 12:10:00.00 UTC
# Prepared by Space Environment Technologies/SpaceWx
# Point-of-contact: W. Kent Tobiska (http://SpaceWx.com)
#
# Metadata:
# Units: Year, Month, Day (YR, MO, DA) are calendar year, integer month, day of month
#        Hour, Minute (HH, MM) are integer hour and minute in UT
#        Julian Day (JD) is the corresponding absolute Julian date
#        Rsn, 3hR = is daily, 3-hour Sunspot number (unitless)
#        E10, 3hE = is daily, 3-hour E10.7
#                    x10-22 Watts per meter squared per Hertz
#        Ap, 3ha = is daily mean and 3-hourly planetary geomagnetic index in 2 nT
#        Kp, 3hk = is daily mean and 3-hourly planetary geomagnetic index (unitless)
#        1sR, 1sE, 1sa, 1sk = is 1 sigma uncertainty in units of those indices
#        SRC = is the source of the data (Historical, Issued, Predicted)
#
# Source: SOLAR2000 OPERATIONAL GRADE V1.21
# Location: SpaceWx {PowerMac MacOS IDL 5.5}
# Missing data: -1
#                        HF Input file
#   CALENDAR         JULIAN
# YR  MO DA HHMM      Day      Rsn E10 A_p K_p 3hR 3hE 3ha 3hk 1sR 1sE 1sa 1sk SRC
#-------------------------------------------------------------------------------------
 2001 09 30 1200 2452183.00000 178 226  48   5 178 226  18   4   8  11  31   0   I
 2001 09 30 1500 2452183.12500 178 226  48   5 178 226  48   5   8  11  31   0   I
 2001 09 30 1800 2452183.25000 178 226  48   5 179 226  67   6  19  11  31   1   I
 2001 09 30 2100 2452183.37500 178 226  48   5 179 227  48   5  20  11  31   1   I
 2001 10 01 0000 2452183.50000 178 226  48   5 179 227  48   5  17  11  31   0   I
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 2001 10 01 0600 2452183.75000 178 226  48   5 179 227  67   6  16  11  31   1   I
 2001 10 01 0900 2452183.87500 178 226  48   5 179 227  67   6  15  11  31   1   I
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 2001 10 01 2100 2452184.37500 180 228  52   6 180 228  48   5  15  10  31   0   P
 2001 10 02 0000 2452184.50000 180 228  52   6 180 229  32   5  17  10  31   0   P
 2001 10 02 0300 2452184.62500 180 228  52   6 181 229  48   5  17  10  31   0   P
 2001 10 02 0600 2452184.75000 180 228  52   6 181 229  67   6  16  10  31   1   P
 2001 10 02 0900 2452184.87500 180 228  52   6 181 229  27   4  16  10  31   0   P
 2001 10 02 1200 2452185.00000 180 228  69   6 181 229  22   4  16  22  31   0   P
 2001 10 02 1500 2452185.12500 180 228  69   6 181 229  32   5  15  22  31   0   P
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