Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons

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Received 18 March 2008; revised 11 July 2008; accepted 11 August 2008; published 18 December 2008.

[1] Simple, one-parameter algorithms are applied to the observed energetic proton flux as provided by instruments aboard the GOES series of satellites to yield estimates of the high-latitude HF and VHF radio wave absorption for day and night, respectively. These results are extended to full daily coverage by treating the effects of solar illumination, geomagnetic cutoff variation, and frequency dependence over the entire earth. Validation calculations of the polar cap absorption of HF radio waves have been performed for 11 larger solar energetic particle events during the period from 1992 to 2002 and the results are compared to observations of 30 MHz riometers operated by the Air Force Geophysics Laboratory and located at Thule, Greenland. Prediction of the minimum event duration from current flux level is also obtained, and a specimen presentation of the north and south polar caps illustrates the graphical output of the model for the peak of the 6 December 2006 solar proton event.

Citation: Sauer, H. H., and D. C. Wilkinson (2008), Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons, *Space Weather*, *6*, S12002, doi:10.1029/2008SW000399.

1. Introduction

[2] The last two decades have witnessed increasing recognition of the impact of the Earth's near-space environment on the technological activities of man. This recognition resulted in the establishment of a National Space Weather Program in 1995. A current analysis of this program and recommendations for its continued development and improvement has been provided by *Office of the Federal Coordinator for Meteorological Services and Supporting Research* [2006]. Among the issues addressed is the transition of scientific information to model development in support of user needs. The global commercial airlines industry represents one of those needs as does the military air community.

[3] Commercial airline transpolar routes were first identified as viable in 1997 with a small number of demonstration flights occurring in the following 2 years. Their route economies produced growth to 6930 cross-polar flights in 2007 (http://helios.swpc.noaa.gov/sww/index.html) with expectations of doubling or tripling of that figure in the next few years. Airlines rely on high-frequency (HF) radio communication at latitudes higher than 82° because of lack of satellite transmission access at these high latitudes. Federal Aviation Regulation (section 121.99) requires continuous radio communication over the entire flight route with dispatch offices and traffic control. Because of the disruption of HF radio transmission during solar energetic proton events, many episodes of flight rerouting or rescheduling have occurred. A United Airlines operations manager has stated that "if polar routes are not available, the additional operating costs and penalties for an unscheduled stop or reroute can total hundreds of thousands of dollars per flight."

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2. Discussion

[4] The precipitation of protons (as well as other ions) into the earth's atmosphere as a consequence of the occurrence of solar energetic particle (SEP) events can create significant enhancement of ionospheric electron densities. Such enhancements are responsible for an increase in the attenuation of electromagnetic waves being transmitted through the ionosphere. In extreme cases the ionosphere may, in fact, be rendered opaque to such transmission.

[5] The mechanism of ionospheric radio wave absorption is well understood. Ionospheric electrons are accelerated by the electric field of the transiting radio wave. In the absence of collisions the electrons would simply reradiate the absorbed energy (with a phase lag because of their inertia). Because of the presence of the neutral atmosphere, the accelerated electrons suffer collisions with the atmospheric constituents and incur an energy loss which results in a reduction of their reemitted signal.

Since the atmospheric density as well as the collision frequency and recombination rate varies with altitude, the efficiency of radio wave absorption in the earth's ionosphere is strongly altitude dependent.

[6] Given observation of the spectrum of the incident proton flux at the top of the atmosphere, the resulting electron density enhancement in the ionosphere is a consequence of the competition between the electrons produced through ionization by the passage of the energetic protons through the atmosphere, and their subsequent loss by recombination and attachment. The rate of ion production per unit path length is a function of the energetic particle spectrum and the atmospheric density while ion loss rate is dependent on the electron neutral collision, attachment and recombination rates which are also functions of the neutral and electron densities.

[7] Because of geomagnetic shielding of the earth, solar protons between the energies of 1–200 MeV, which are responsible for most of the ionospheric absorption of HF radio waves, find easy access to the atmosphere in high-latitude regions around the earth's geomagnetic poles. Such occurrences were therefore termed Polar Cap Absorption (PCA) events [*Bailey*, 1964]. However, the latitudinal extent of the polar cap is determined by the disturbance level of the geomagnetic field, which is typically characterized by the geomagnetic index *Kp*.

[8] As indicated, there are several physical processes that enter into the quantitative estimation of ionospheric radio wave absorption. Determination of the rate of ion pair production due to the propagation of energetic particles through the atmosphere requires knowledge of the input particle spectrum which is best provided by direct satellite observation as well as a competent model of the atmospheric density. These requirements are well met. The situation with respect to the determination of the effective recombination coefficients which determine the resulting electron density profiles is considerably more uncertain. These parameters depend upon a complex atmospheric chemistry [*Patterson et al.* 2001; *Kavanaugh et al.*, 2004; *Hunsucker and Hargreaves*, 2008], which depend upon altitude, time of day, season, and solar illumination. An important consequence of these dependences is that the daytime and nighttime recombination and detachment rates are significantly different and therefore result in quite different levels of absorption for same incident energetic particle spectrum [*Hunsucker and Hargreaves*, 2008].

3. Model Elements

3.1. Specifying the Input Solar Proton Flux

[9] The SMS-GOES series of satellites operated by the NOAA Space Weather Prediction Center (SWPC) have provided monitoring of the energetic particle environment at geostationary orbit since 1974. Determinations of the integral flux of protons at seven threshold energies ($E > 1$, 5, 10, 30, 50, 60, and 100 MeV) may be found on their website (swpc.noaa.gov) along with information about these data and the instruments and platforms which provide them. These data are available at a 5-min cadence and acceptance of these data in providing the solar proton spectral input to the present model is desirable because of their long-term consistency and availability.

[10] *Murata and Muraki* [2001] have demonstrated the equivalence of EXOS-D observations of greater than 7 MeV proton fluxes over the polar caps and those of the GOES-6 satellite at geostationary. The observed equivalence serves to validate the use of the GOES observations to represent the flux of solar protons entering the high-latitude ionosphere, at least at these energies. This equivalence also supports the essential isotropy of the flux and its uniformity over the spatial scale of the magnetosphere; characteristics which are assumed by the model. Below energies of 7 MeV, however, it is expected that a finite cutoff energy would operate, at least during magnetically quiet times and early in the event. Examination of the spectra of the 15 largest solar particle events of the period 1997–2002 [*Sauer*, 2003] demonstrates no large spectral anomalies at energies as low as 1 MeV after the initial hours to a day or so, which would suggest the absence of significantly restricted access of low-energy solar particles to geostationary orbit after this initial phase. It is also to be noted that the $E > 1$ MeV channel data will always include a trapped particle contribution and that the $E > 5$ MeV channel may include a trapped component during periods of geomagnetic activity, which also compromises the ability to accurately determine solar particle flux levels in these energy ranges. This constitutes a principal rationale for the model's use of first-order approximations to its component elements.

3.2. Absorption Estimate

[11] The association of a strong ionospheric response with solar energetic particle events was established following the major event of 23 February 1956 [*Bailey*, 1957]. Because of geomagnetic restriction of the incoming protons to a circle about the geomagnetic poles, the resulting increase in ionospheric radio wave absorption in these regions was termed PCA (Polar Cap Absorption). The riometer (Relative Ionospheric Opacity METER) was developed by *Little and Leinbach* [1963] and is a radio receiver, which observes cosmic radio noise in the UHF/VHF regime (typically 30 MHz) and its absorption in passing through the ionosphere. After establishing the proportionality of the square of the absorption to the integral proton flux impinging on the atmosphere, a number of workers [cf. *Kavanaugh et al.*, 2004 and references therein] developed expressions for daytime absorption as a function of the integral proton flux, $J(E)$ (given in $(\mathrm{cm^2\ s\ sr})^{-1}$) above some threshold energy E_o of the form $A = k\{J(E > E_o)\}^{1/2}$, where the absorption A is expressed in decibels and k is a constant. *Sellers et al.* [1977] examined a number of events and first established expressions for the 30 MHz absorption

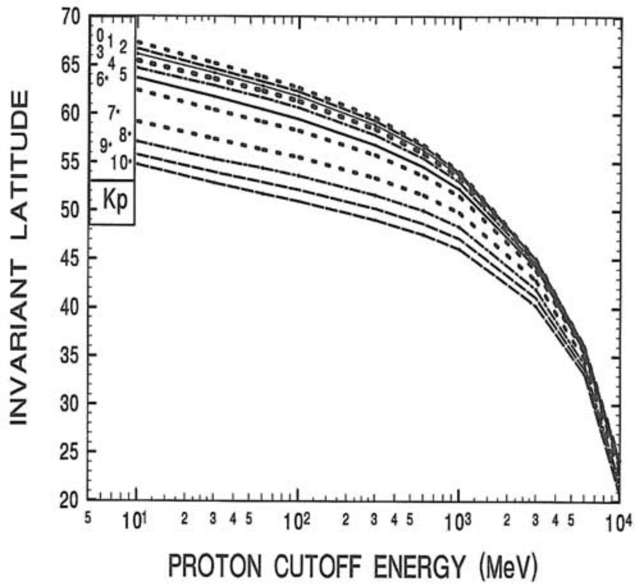

Figure 1. Proton cutoff energy versus invariant latitude as a function of geomagnetic activity K_p.

of the stated form for both and night conditions respectively. They are given byDaytime Abs

$$A_d = 0.115[J(E > 5.2\,\mathrm{MeV})]^{1/2} dB \tag{1a}$$

Nighttime Abs

$$A_n = 0.020[J(E > 2.2\,\mathrm{MeV})]^{1/2} dB. \tag{1b}$$

These expressions have been adopted for use of the model. The twilight response remains unspecified as yet. It is clear that the twilight response is highly variable [cf. *Sauer*, 1968; *Kavanaugh et al.*, 2004], dependent on

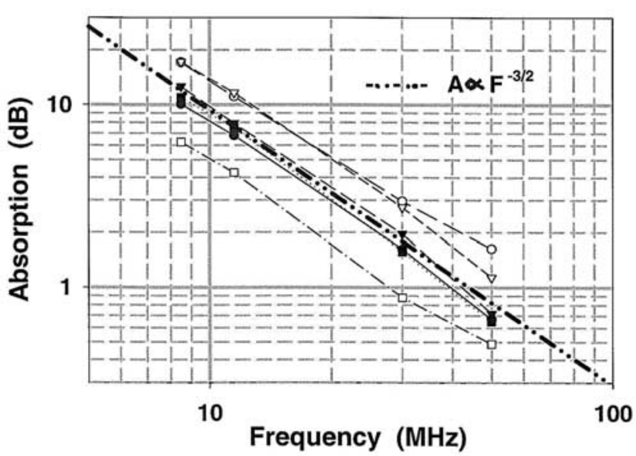

Figure 2. Transionospheric absorption versus frequency.

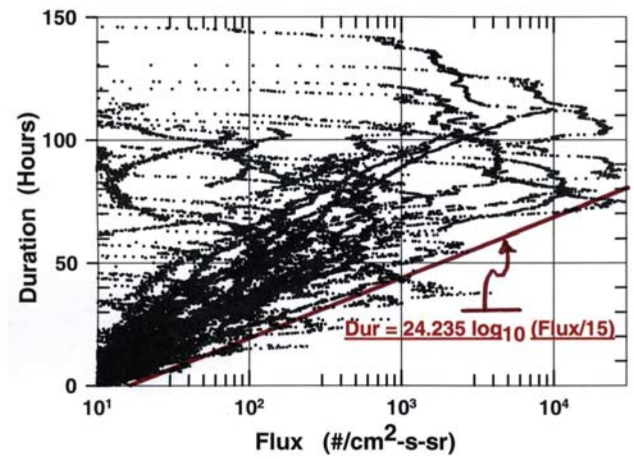

Figure 3. Integral flux J = (E > 10 MeV) versus the remaining event duration for 11 events. The red line denotes the duration prediction Dur given by the indicated expression.

geographic location, season, and the state of the ionosphere and its chemistry. A heuristic approach has been taken for the model in that it is assumed that daytime is fully established at a solar elevation angle El of $\geq 10°$, with night fully established at a solar elevation angle El of $\leq -10°$. Between these limits, the twilight absorption at 30 MHz, A_{30} is obtained as a bilinear composition of the daytime absorption. A_d and nighttime absorption A_n

$$A_{30} = Ad(El + 10°)/20° - An(El - 10°)/20° dB. \tag{2}$$

This value comprises the model estimate of the absorption in decibels A_{30} at a frequency of 30 MHz, appropriate for the polar cap (high geomagnetic latitude) region where the geomagnetic field imposes little interference to energetic particle entry.

3.3. Geomagnetic Cutoff Effects

[12] The geomagnetic field of the earth requires that an energetic particle entering the earth's magnetosphere

Table 1. Dates and Times of Selected Events

Event	Date	Time (in UT)
1	20 April 1998	1400
2	14 July 2000	1045
3	8 November 2000	1555
4	2 April 2001	2340
5	15 April 2001	1410
6	24 September 2001	1215
7	1 October 2001	1145
8	4 November 2001	1705
9	22 November 2001	2320
10	26 December 2001	0605
11	21 April 2002	0225

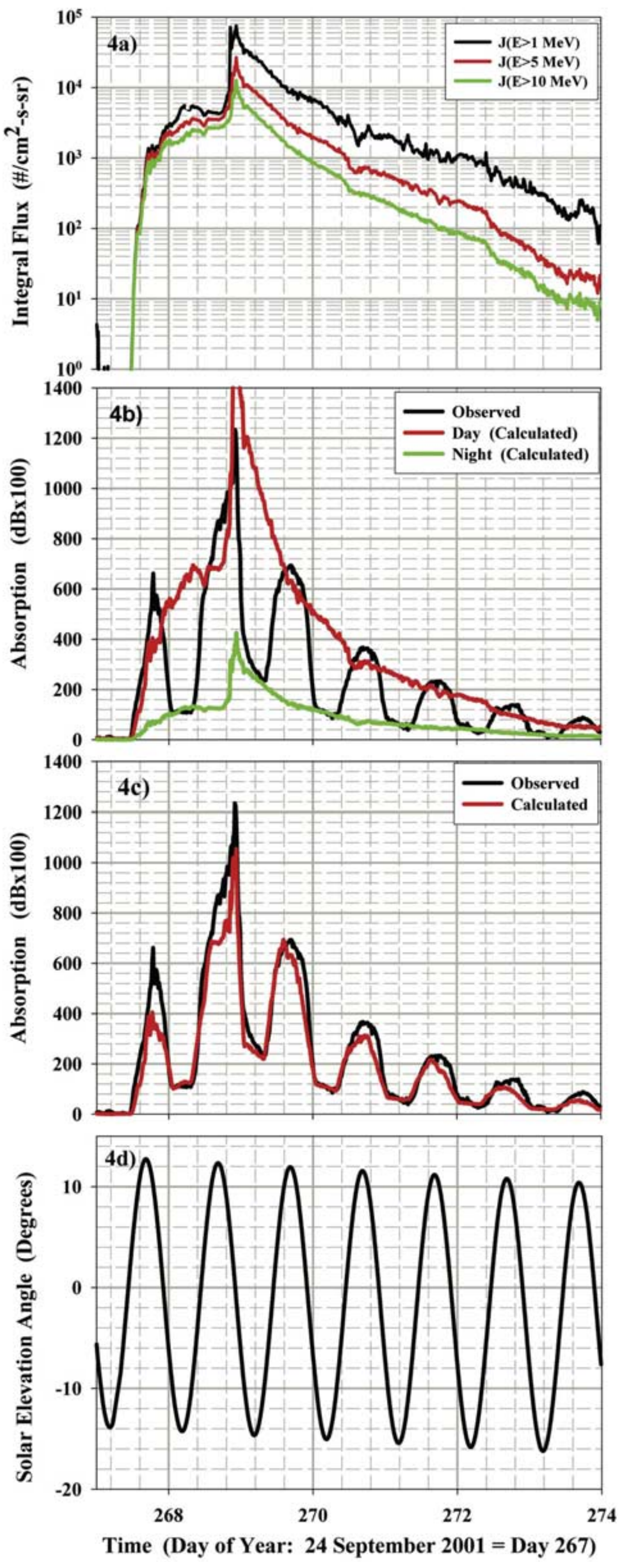

Figure 4. Model output development for SEP of 24 September 2001. (a) GOES-8 with $E > 1$, $E > 5$, and $E > 10$ MeV integral fluxes. (b) Comparison of observed 30-MHz absorption with calculated day and night absorption values. (c) Comparison of observed 30-MHz absorption with calculation including model solar illumination effect at Thule. (d) Solar elevation angle at Thule during event of 24 September 2001.

possess a minimum energy E_c termed the cutoff energy, in order to reach a specific point of arrival from a specific direction; conventionally the vertical direction. Through numerical calculations of particle trajectories in a competent model of the magnetospheric fields around the earth, *Smart et al.* [1999] have computed the changes of the vertical cutoff energy at an altitude of 450 km for many levels of geomagnetic activity, as represented by the magnetic index K_p. Their results are shown in Figure 1 in terms of invariant latitude. The invariant latitude is derived from the McIlwain L parameter [*McIlwain*, 1961], which reasonably characterizes the internal geomagnetic field at subauroral latitudes (about ±65°) in terms of an equivalent dipole field. Given L, the invariant latitude λ is found from the equivalent dipole expression

$$R = L\cos^2\lambda, \tag{3}$$

where R (the radial distance often taken to be 1 R_E at the earth's surface) and L are both given in earth radii (R_E = 6371 km). *Smart et al.*'s [1999] determinations were made for an altitude of 450 km (R = 1.0706 R_E), and expression (3) is used to determine the approximate latitude shift resulting from propagation along the field line characterized by the value L from the altitude of 450 km (1.0706 R_E) to an altitude of 50 km (1.0078 R_E) which is adopted as representing the region of the ionosphere addressed by the model, i.e.,

$$d\lambda = \pm dR/(2L\sin\lambda\cos\lambda)\mathrm{rad} \tag{4}$$

is then the poleward shift of the invariant latitude due to a reduction in altitude of dR.

[13] Given a location of interest determined by the above procedure to have an operative geomagnetic cutoff energy E_c, which is above one or both of the energy thresholds of equations (1a) and (1b), the affected term $J(E > 2.2$ MeV) and/or $J(E > 5.2$ MeV) would be replaced by $J(E > E_c)$ in order to include only those protons able to reach that position.

[14] In order to provide a continuous spectral representation of the proton flux data provided by GOES, a power law representation ($J = JoE^{-\gamma}$) was determined between adjacent pairs of data. The fit from the $J(E > 60$ MeV) to the $J(E > 100$ MeV) channel was used to extrapolate to E = 200 MeV, the adopted energy limit. Protons above an

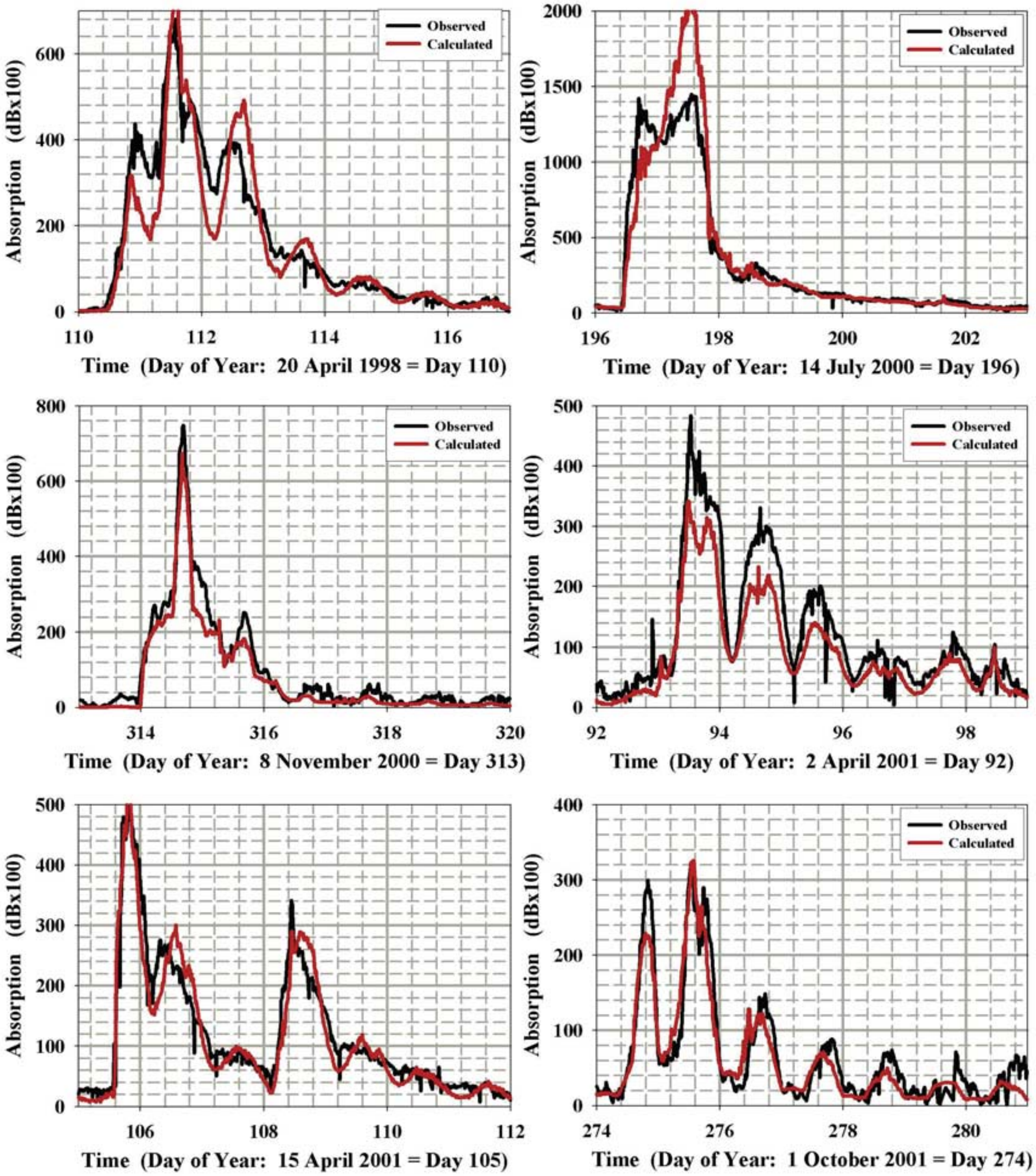

Figure 5a. Calculated versus observed (Thule) results for the first six events of Table 1.

energy of 200 MeV provide negligible ionospheric absorption, primarily because of the solar proton flux decrease with energy [*Patterson et al.* 2001; *Kavanaugh et al.*, 2004].

3.4. Frequency Dependence of Absorption 227

[15] *Parthasarathy et al.* [1963] studied radio wave absorption using a multifrequency riometer at frequencies of 10, 30, and 50 MHz. Through analysis of their data, J. K. Hargreaves, (private communication, 2008) has shown (Figure 2) that the absorption Af at a frequency f other than 30 MHz is well represented by a dependence of ionospheric absorption on the inverse 1.5 power of the frequency, i.e.,

$$Af = (30/f)^{1.5} A_{30}. \tag{5}$$

This result is consistent with theoretical determination of the daytime absorption as a function of frequency for various incoming proton energies as provided by *Patterson et al.* [2001] over a comparable frequency range. While these results have been established specifically for daylight

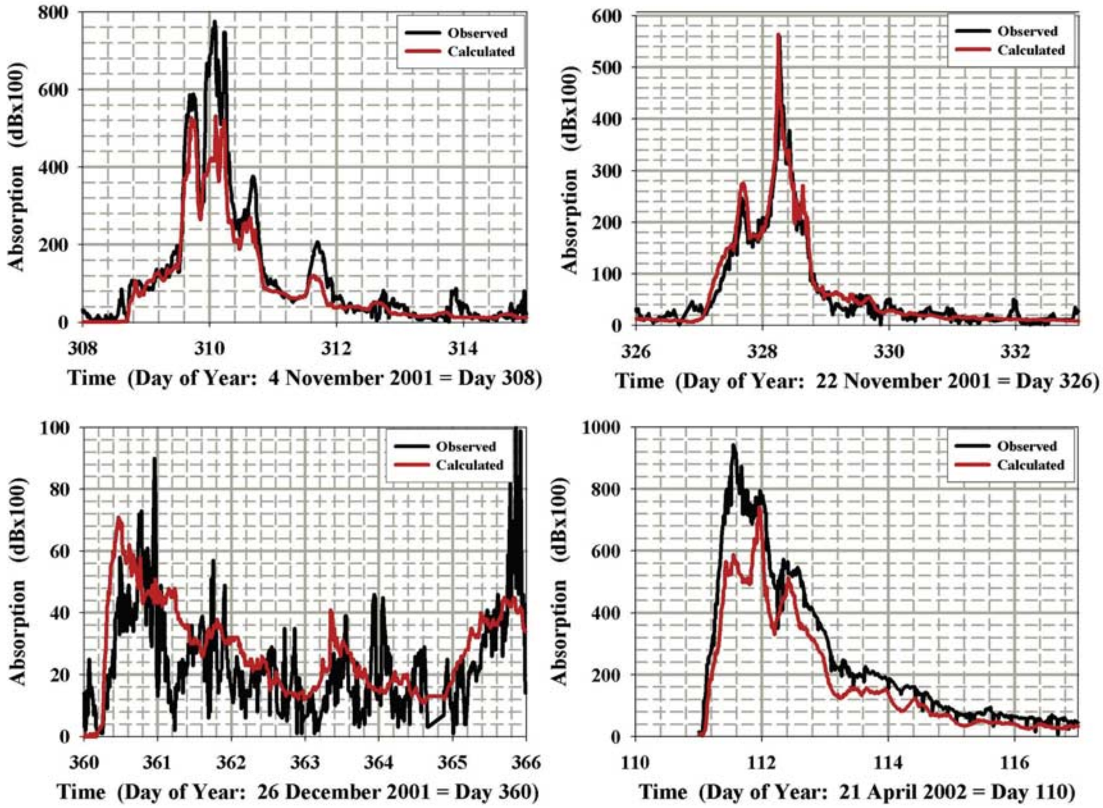

Figure 5b. Calculated versus observed (Thule) results for remaining four events of Table 1.

conditions it will be adopted for nighttime use as well in view of the much lower ionospheric response at night, making any error correspondingly less significant.

3.5. Event Duration Prediction

[16] It is desirable that some estimate of the duration of ionospherically significant solar energetic particle events be made. All comparisons of event durations with event characteristics have been found to exhibit such large variation that they are of little value in the estimation of event duration. However, a relationship has been determined which provides a prediction of the minimum duration of the event with quite high reliability. Figure 3 plots the 5-min values of the GOES reported integral flux greater than 10 MeV versus the time to the SEP event end for the 30 largest events (flux > 300/cm^2 s sr) of the 7-year period from 1997 to 2003. The red line indicates the minimum time to event end as given by the expression for the remaining event duration Dur

$$\mathrm{Dur} = 24.235 \log_{10}(\mathrm{flux}/15)\mathrm{h}. \qquad (6)$$

The points lying below the prediction curve represent the underestimates of duration predictions which primarily result from local and/or transitory anisotropies. These "failures" comprise 2% of the total samples. It is to be remembered that the event criterium adopted here is that of the NOAA SWPC which requires a greater than 10 Mev flux of at least 10 protons per cm^2 s sr, while the absorption is dependent on fluxes at energies as low as 2.2 MeV. Therefore the prediction is in fact very conservative and experience may relax the criterium while retaining its high degree of reliability. It is also to be noted that the projections during the rising phase of the event will necessarily be strong underestimates until the peak flux has been encountered. A majority of events will, however, have much shorter rise than decay times thereby removing uncertainty from that cause relatively quickly.

4. Model Results

[17] The 30 MHz Thule riometer observations were obtained from K. Walker compliments of the Air Force Research Laboratory for 11 of the larger SEP events during the period 1998–2002. Corresponding SEP event data were obtained from the GOES archives of the NOAA National Geophysical Data Center (goes.ngdc.noaa.gov/data/avg). The SEP event start dates and times are given in Table 1.

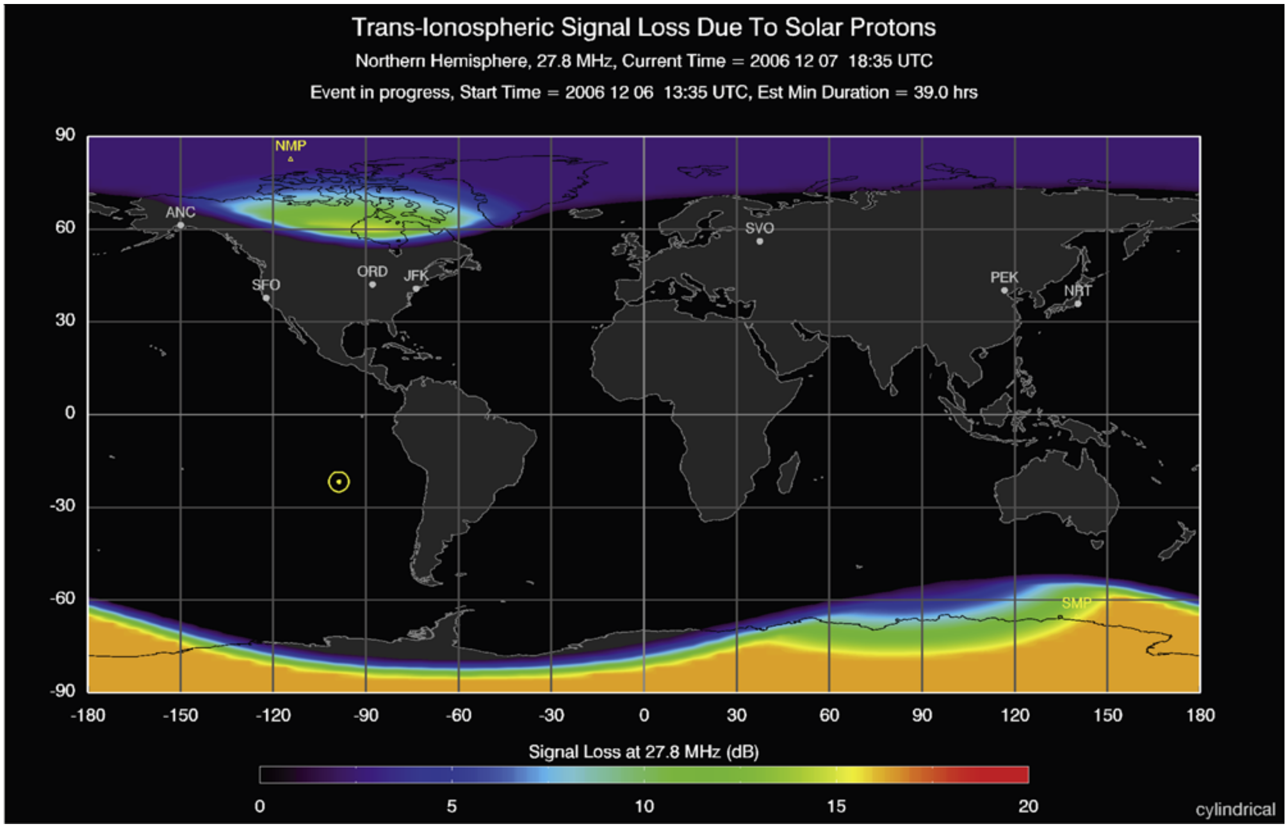

Figure 6. Specimen model output in cylindrical (latitude-longitude) projection for peak of the 6 December 2006 SEP event.

[18] Figure 4 illustrates the model result development for 30 MHz Thule riometer observations during the near-equinoctal SEP event of 24 September 2001, which extends equally over both day and nighttime conditions. Figure 4a shows the GOES-8 proton fluxes observed for the following three lowest proton energy thresholds: $E > 1$, $E > 5$, and $E > 10$ MeV. In Figure 4b, the Thule observed 30 MHz absorption is plotted with the model day and nighttime absorption estimates of equations (1a) and (1b). It is noted that the estimate discrepancy reaches approximately 50% during the first day, reducing significantly thereafter. While conceivably due to local anisotropies, this discrepancy is probably primarily due to restricted entry of the lowest-energy protons to geostationary orbit until later in the event, as had been previously noted. Figure 4c presents the final model absorption estimate after having applied the assumed twilight response (equation (2)) to the solar illumination illustrated in Figure 4d. Figures 5a and 5b. summarize the model calculations for the remainder of events of Table 1 and their comparison to the Thule 30 MHz riometer observations.

5. Dynamic Model Implementation

[19] For absorption estimate outside the polar cap, the L value [*McIlwain*, 1961] is calculated for that location using the Shellig code provided by National Space Science Data Center, and the estimated Kp value obtained from the NOAA-SWPC and produced by the U.S. Air Force, These are used together with the information on the variation of cutoff latitude with respect to Kp provided in Figure 1 [*Smart et al.*, 1999] to produce the result at the frequency of interest to the user.

[20] In the model's global application, calculations are made at a resolution of 2° in latitude by 4° in longitude. This resolution is deemed not inconsistent with the accuracy of the calculations involved while providing smooth image contours. It is to be noted that the model currently takes as its result twice the vertical ionospheric transit absorption in order to provide a reasonable surrogate for the typical case of HF/VHF signal propagation at an angle to the vertical and reflected by the ionosphere and therefore passing twice through the lower ionosphere. Figures 6 and 7 provide specimen global graphic model outputs in latitude-longitude and polar projections, respectively, for the SEP event of 6 December 2006 near its peak at 1207 UT on 7 December.

[21] It is expected that such a determination and display will become an operational product of the SWPC website in 2008, to be evaluated and presented at the 5-min cadence of the GOES particle data. Information about

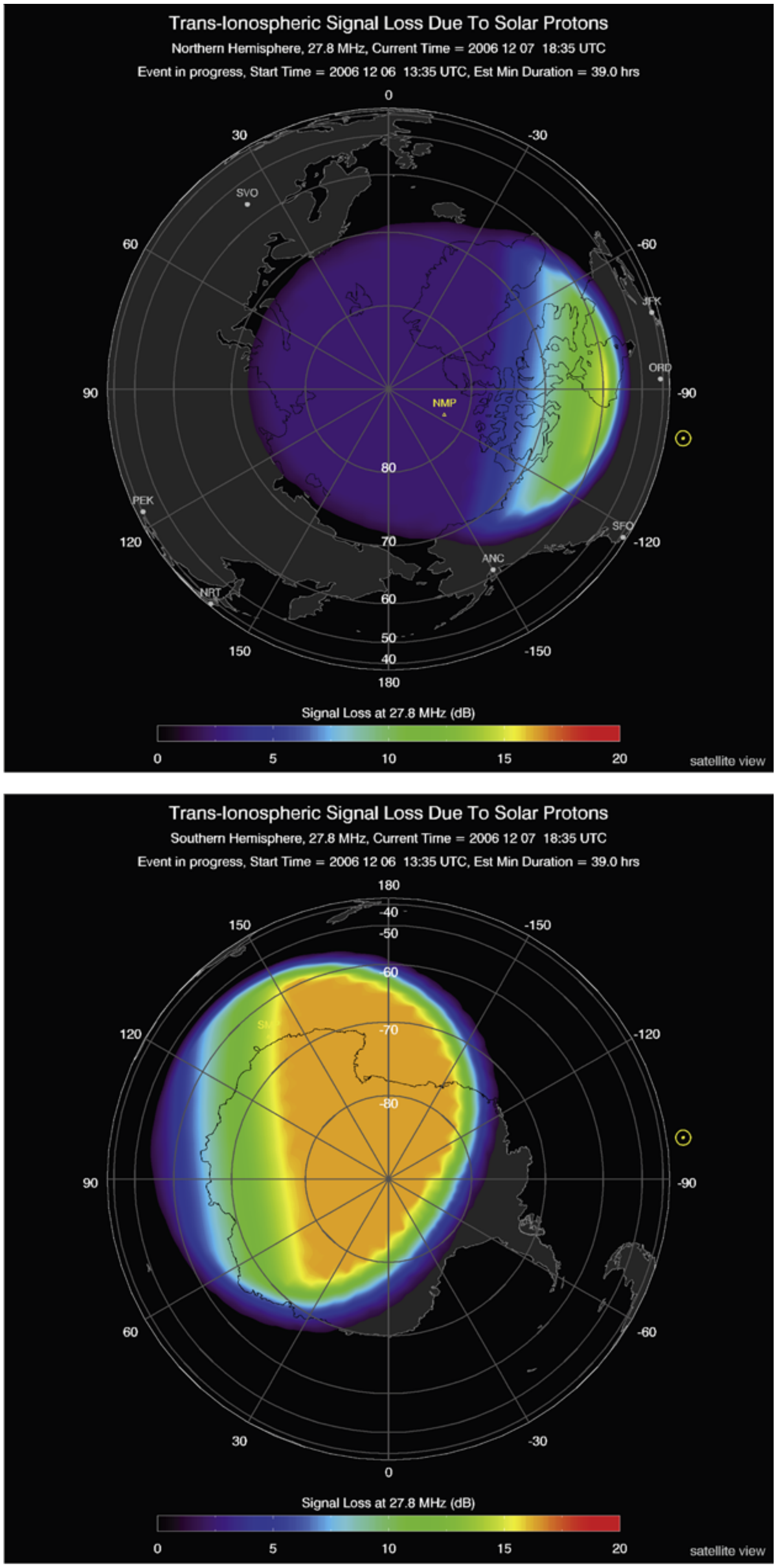

Figure 7. Specimen model output polar views for peak of the 6 December 2006 SEP event.

the event is dynamically provided within the displays, such as: event status, start time, current time, HF/VHF absorption, evaluation frequency, and the minimum event duration, as well as the position of the sun. Future experience will then allow determination of any benefit or necessity for model improvement over the simple procedures used here.

6. Model Improvement

[22] Although the model estimates are of sufficient accuracy to be of value, several improvements have been considered which might increase its accuracy. Clearly, the largest quantitative improvement would be the provision of data collected outside the magnetosphere or above the polar caps to avoid the contamination of the trapped particle contribution to the lower GOES data channels. It would appear unlikely, however, to have an interplanetary monitor in the near term that would possess the long-term convenience, stability and coverage of the GOES series. Also as true for a polar orbiter and further unlikely; a number of spacecraft at different orbital phases that would be necessary to provide essentially continuous coverage over the polar caps. Better accuracy during the dawn-dusk solar illumination period would be expected from a more sophisticated transition relationship than the bilinear composition currently used, however, such a change would primarily impact the estimated absorption at less that maximum levels.

[23] The relationship between proton flux and absorption is dependent on the spectral characteristics as well as the integral flux alone. It would appear that determination of the dependence of the absorption on spectral hardness as well would provide a significant improvement, however both *Sellers et al.* [1977] and *Kavanaugh et al.* [2004] remark on the relative insensitivity of their results to spectral hardness.

[24] It is expected that such a determination and display will become an operational product of the SWPC website in 2008, to be evaluated and presented at the 5-min cadence of the GOES particle data. Information about the event is dynamically provided within the displays, such as event status, start time, current time, HF/VHF absorption, evaluation frequency, and the minimum event duration. Future experience will then allow determination of any benefit or necessity for model improvement over the simple procedures used here.

[25] **Acknowledgments.** We are grateful to the NOAA Space Weather Prediction Center for availability of the GOES energetic particle data and to acknowledge the initial graphical display coding provided by Michael Husler of the NOAA SWPC. We also gratefully acknowledge receiving the Shellig *L* computation from D. Bilitza at NASA's NSSDC/SPDF and the provision of Thule 30 MHz absorption data by Kenneth Walker, compliments of the Air Force Research Laboratory, Space Weather Center of Excellence, Hanscom Air Force Base, Massachusetts. Funding for the riometers is provided by the Air Force Weather Agency.

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