D-RAP Model Validation: I. Scientific Report

R. A. Akmaev for the Validation Team
(A. Newman, M. Codrescu, C. Schulz, E. Nerney)

Introduction

The purpose of this report is to summarize the results of an effort undertaken for the D-Region Absorption Prediction (D-RAP) Validation and Testing Project to evaluate the performance of the model with respect to observations at several riometer stations during a representative set of historic events. The now operational D-RAP model combines two empirical models of absorption of high-frequency (HF) radio waves in the ionospheric D-region: the formerly operational global X-ray absorption model and a recently developed model of polar-cap absorption (PCA) due to solar energetic proton (SEP) precipitation (Sauer and Wilkinson, 2008). Note however that currently there exist no suitable parameterization of the auroral absorption, which may result in substantial underestimation of total absorption at high- and mid-latitudes.

The two component models calculate absorption at a default frequency f_0, currently set to 10 MHz, at 1-min and 5-min intervals for X-ray flares and proton precipitation events, respectively. The combined absorption is assumed to be simply a sum of the two components. It is thus created at 1-minute cadence and assigned the same valid time stamp as the X-ray component, provided both absorption components are available. If either of the two model components is not available, the combined total absorption has not been generated for the purpose of this validation.

The second part of this report presents findings on the D-RAP software design, implementation, and deficiencies (bugs) and provides recommendations on its possible future improvements.

Validation procedure

Within the validation project the output of the model is compared to riometer observations from a set of high- to mid-latitude stations during several validation periods consisting of SEP and X-ray flare events. The total model absorption A_0 is converted to the riometer frequency f_r using the following relation (e.g., Sauer and Wilkinson, 2008):

$$A(f_r) = A_0(f_0/f_r)^{3/2}. \qquad (1)$$

For each station and validation period two kinds of plots have been generated: time series of observed and total model absorption and scatter plots of modeled vs. observed absorption. Simple statistical characteristics have been calculated (at the frequency of the riometer): the model absorption root-mean-square error (RMSE), model bias (mean error), mean observed absorption, relative model error, and relative model bias. Individual statistics are available for each station and validation period. The same statistics have also been calculated for each station cumulatively over all validation periods with available station data. For these comparisons the model output has been taken from a point on the model grid (2°×4° in latitude-longitude) nearest the location of the observing station. For pairwise comparison (scatter) plots and statistical calculations the model output additionally had to be within 1 min of the observed value.

Observations

Table 1 lists the riometer stations chosen for the validation study. This project thus substantially expands the coverage compared to the study of Sauer and Wilkinson (2008), which validated the SEP absorption model on data available from only one high-latitude station (Thule). The addition of European stations enables the validation of the model in other longitude sectors while the extension of coverage to mid-latitudes potentially provides an opportunity to validate the X-ray component model provided that the station in question is on the dayside during a flare event.

Table 1. Riometer stations used in validation.

	Station	Latitude	Longitude	Frequency
1	Thule, Greenland	77.50° N	69.20° W	30.0 MHz
2	Taloyoak, Canada	69.54° N	93.55° W	30.0 MHz
3	Rovaniemi, Finland	66.78° N	25.94° E	32.4 MHz
4	Dawson, Canada	64.05° N	139.11° W	30.0 MHz
5	Jyväskylä, Finland	62.42° N	25.28° E	32.4 MHz
6	Pinawa, Canada	50.20° N	96.04° W	30.0 MHz

Table 2 lists the 13 particle precipitation events for which the model has been run. The first 11 events through the year 2002 are the same as considered by Sauer and Wilkinson (2008). Two events in 2005 accompanied by X-ray flares were added to possibly validate the X-ray component model. Unfortunately, it was impossible to obtain data from any of the stations (Table 1) for the last period within the time frame of this project. The total number of station-validation period combinations is 60 compared to 11 in the study of Sauer and Wilkinson (2008).

Table 2. Validation periods.

	Start date	Stations	X-rays
1	April 20, 1998	1, 2, 4, 6	yes
2	July 14, 2000	1, 2, 4, 6	yes
3	November 8, 2000	1, 2, 4, 6	
4	April 2, 2001	1 – 6	yes
5	April 15, 2001	1 – 6	
6	September 24, 2001	1 – 6	
7	October 1, 2001	1 – 6	
8	November 4, 2001	1 – 6	yes
9	November 22, 2001	1 – 6	yes
10	December 26, 2001	1, 2, 3, 4, 5	yes
11	April 21, 2002	1, 2, 4, 6	
12	January 19, 2005	2, 4, 6	yes
13	September 6, 2005	none	yes

Further details of the validation procedure, definitions, and numerical calculations may be found in the D-RAP Validation and Testing (V&T) Project Requirements document.

Findings

Comparison with observations

Tables 3 – 8 list the statistical characteristics of model-data comparisons for each station in the order they are listed in Table 1 and every validation period, for which the station data are available. Additionally, the bottom row of each table contains cumulative statistics over all validation periods available for a given station.

Table 3. Station statistics: Thule (30 MHz)

Period	RMSE (dB)	Bias (dB)	Mean (dB)	Rel. Err. (%)	Rel. Bias (%)
1	0.4	-0.1	1.9	19.5	-3.1
2	3.2	1.3	3.3	95.0	39.9
3	0.4	-0.2	1.0	37.9	-22.5
4	0.3	-0.1	1.3	21.9	-8.6
5	0.2	0.0	1.2	19.0	1.3
6	0.4	0.0	2.5	17.5	-0.6
7	0.2	0.0	0.7	31.3	2.3
8	0.6	-0.3	1.3	51.4	-24.2
9	0.2	0.0	0.7	27.3	3.3
10	0.2	0.0	0.3	59.8	18.9
11	0.5	-0.2	2.3	20.7	-7.6
Cumulative	1.1	0.1	1.5	69.2	3.8

Table 4. Station statistics: Taloyoak (30 MHz)

Period	RMSE (dB)	Bias (dB)	Mean (dB)	Rel. Err. (%)	Rel. Bias (%)
1	0.6	-0.3	1.7	33.7	-17.1
2	5.0	2.6	2.0	242.9	125.5
3	1.0	0.3	0.8	124.7	37.8
4	0.3	0.1	1.0	30.0	8.1
5	0.4	0.3	0.5	81.8	65.0
6	1.5	0.3	2.4	63.8	14.2
7	0.3	-0.1	0.9	32.8	-7.7
8	0.9	-0.3	1.6	54.2	-15.8
9	0.7	0.4	0.5	131.1	78.1
10	0.3	0.2	0.2	165.7	128.3
11	1.2	0.5	1.2	99.1	39.9
12	0.4	0.0	0.5	69.1	-8.9
Cumulative	1.7	0.4	1.2	144.1	30.6

Table 5. Station statistics: Rovaniemi (32.4 MHz)

Period	RMSE (dB)	Bias (dB)	Mean (dB)	Rel. Err. (%)	Rel. Bias (%)
4	0.7	-0.4	0.6	107.3	-72.0
5	0.6	-0.4	0.6	95.5	-60.6
6	1.1	-0.6	1.2	94.5	-51.9
7	0.8	-0.4	0.7	115.2	-56.0

8	1.0	-0.3	0.9	111.6	-39.5
9	1.3	-0.2	0.8	160.2	-24.1
10	0.3	-0.2	0.2	135.2	-83.6
Cumulative	0.9	-0.4	0.7	120.2	-51.9

Table 6. Station statistics: Dawson (30 MHz)

Period	RMSE (dB)	Bias (dB)	Mean (dB)	Rel. Err. (%)	Rel. Bias (%)
1	0.5	0.0	1.0	46.6	-4.1
2	5.3	2.1	1.7	307.5	118.5
3	1.4	-0.2	1.3	101.8	-15.5
4	0.9	-0.5	1.2	75.0	-41.6
5	0.6	-0.4	1.1	57.7	-34.9
6	2.7	0.5	1.6	170.4	30.8
7	0.5	-0.1	0.8	68.5	-9.4
8	2.4	0.3	1.5	155.9	17.0
9	0.4	-0.1	0.8	45.9	-7.0
10	0.4	-0.2	0.4	121.8	-49.2
11	0.4	0.0	1.2	31.3	-3.2
12	1.3	-0.8	1.2	109.4	-67.2
Cumulative	2.0	0.1	1.2	173.4	6.6

Table 7. Station statistics: Jyväskylä (32.4 MHz)

Period	RMSE (dB)	Bias (dB)	Mean (dB)	Rel. Err. (%)	Rel. Bias (%)
4	0.2	-0.2	0.2	107.8	-81.0
5	0.3	-0.2	0.3	126.5	-75.7
6	0.4	-0.3	0.3	128.2	-83.4
7	0.4	-0.3	0.3	131.2	-91.2
8	0.7	-0.2	0.4	182.4	-47.6
9	1.2	0.1	0.3	476.1	21.3
10	0.2	-0.1	0.1	126.4	-99.1
Cumulative	0.6	-0.2	0.3	227.5	-61.5

Table 8. Station statistics: Pinawa (30 MHz)

Period	RMSE (dB)	Bias (dB)	Mean (dB)	Rel. Err. (%)	Rel. Bias (%)
1	0.4	-0.3	0.3	161.4	-95.8
2	4.6	0.7	1.1	428.9	66.8
3	0.8	-0.4	0.4	186.5	97.5
4	0.5	-0.2	0.3	150.0	-79.9
5	0.4	-0.2	0.2	182.7	-84.5
6	2.0	-0.2	0.5	378.2	-30.1
7	1.4	-0.8	0.9	152.9	-86.6
8	1.7	-0.8	1.2	140.6	-68.5
9	0.8	-0.3	0.6	133.8	-43.2
11	0.4	-0.2	0.3	150.9	-93.4

12	0.9	-0.4	0.6	155.1	-72.5
Cumulative	1.8	-0.2	0.6	319.7	-44.3

Because the SEP absorption model was specifically developed and tuned based on historic Thule riometer data (Sauer and Wilkinson, 2008), on average the model performs reasonably well at this location (e.g., Fig. 1) in terms of both the RMS error and bias (Table 3). Interestingly, however, period 2 (July 2000) stands out at this station in that the model substantially overestimates the peak absorption (Fig. 2), resulting in both a large error and positive bias over the whole period. Similar behavior is registered at other high-latitude stations in the American sector, e.g., Taloyoak and Dawson, for this and a few other periods (e.g., Figs. 3 and 4).

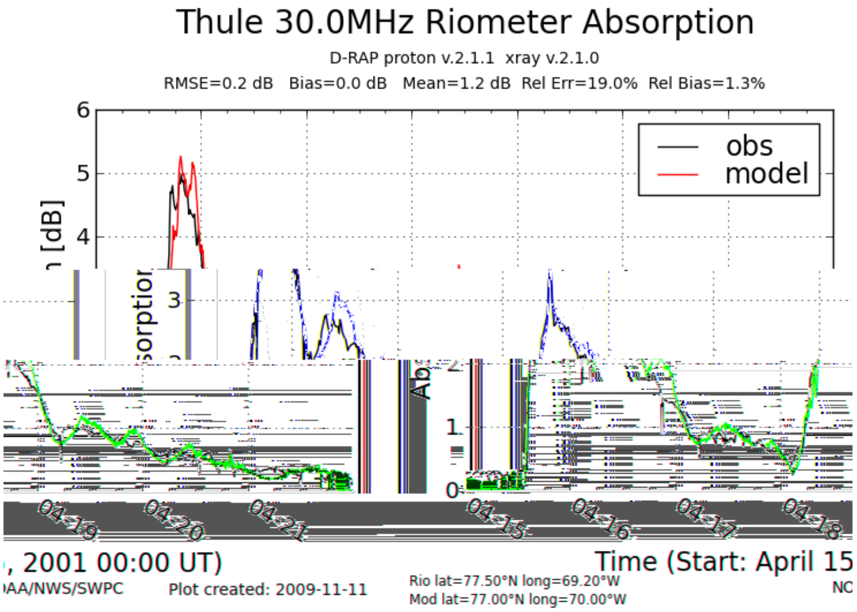

Figure 1. Comparison of model and riometer absorption at Thule for period 5.

Note that comparatively large relative errors and biases are in part due to small mean values over the validation periods as the observed absorption diminishes over time after peaking during the onset of an event. One has to keep in mind however that according to (1) small absolute errors at typical riometer frequencies of about 30 MHz will translate into much larger errors at lower frequencies. For example, the absorption and its absolute error will increase roughly by a factor of 5 at 10 MHz and by almost a factor of 15 at 5 MHz. Also, by design riometers measure the absorption along a ray path crossing the D-region once, while in communication applications the radio signal typically crosses the D-region twice introducing another factor of 2 in both the absolute absorption values and errors.

Riometer stations in the European sector appear to exhibit systematic underestimation of model absorption (Tables 5 and 7). Figures 5 and 6 show the results at Rovaniemi and Taloyoak, where the model substantially underestimates and overestimates the absorption, respectively, during the same period 10 (December 2001). This comparison suggests that the geomagnetic energy cutoff at subauroral latitudes as suggested by Sauer and Wilkinson (2008) may need further tuning on more geographically representative data to adequately predict absorption in different longitude sectors.

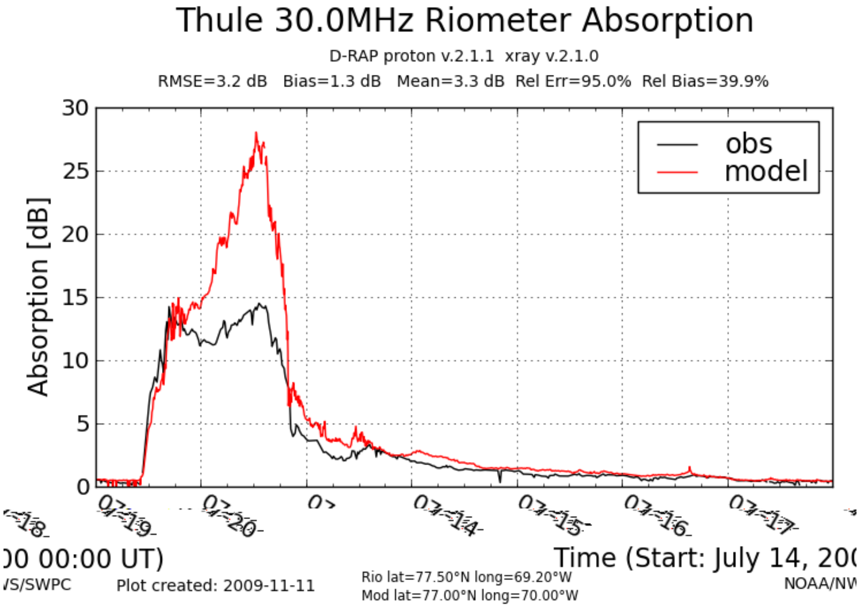

Figure 2. Same as in Fig. 1 but for period 2.

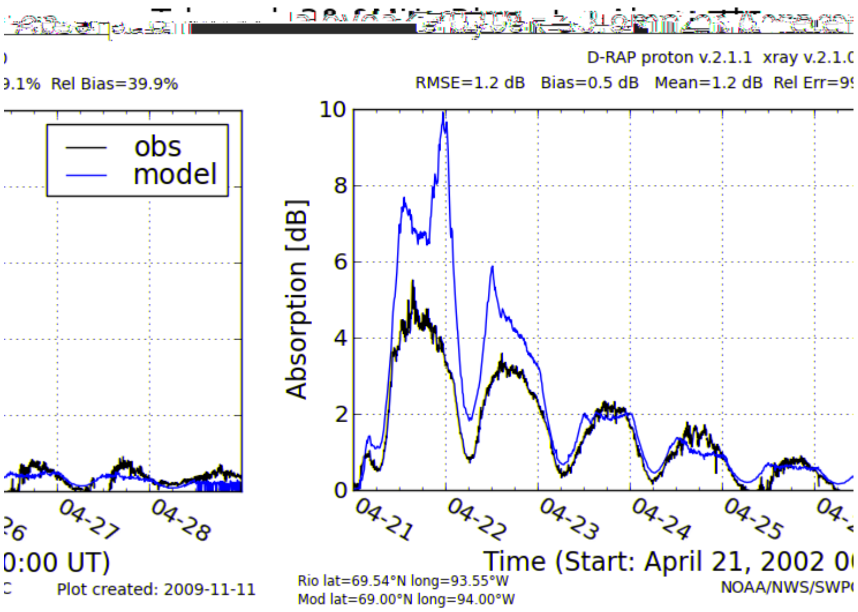

Figure 3. Comparison of model and riometer absorption at Taloyoak for period 11.

Absorption at a midlatitude station (Pinawa) appears to be also systematically underestimated (Table 8). A possible source of the underestimation here appears to be the lack of parameterization of absorption due to auroral particle (electron) precipitation in the model (e.g., compare the second half of period 1 at Thule and Pinawa in Figs. 7 and 8, respectively). This additional source of ionospheric absorption cannot be predicted by the current model. It should be noted here that there exist operational models and products for predicting auroral activity, at least in a statistically climatological sense, based on geomagnetic activity (e.g., http://www.swpc.noaa.gov/pmap/index.html). A similar approach should be explored for operationally predicting the attendant ionospheric absorption due to auroral particle precipitation.

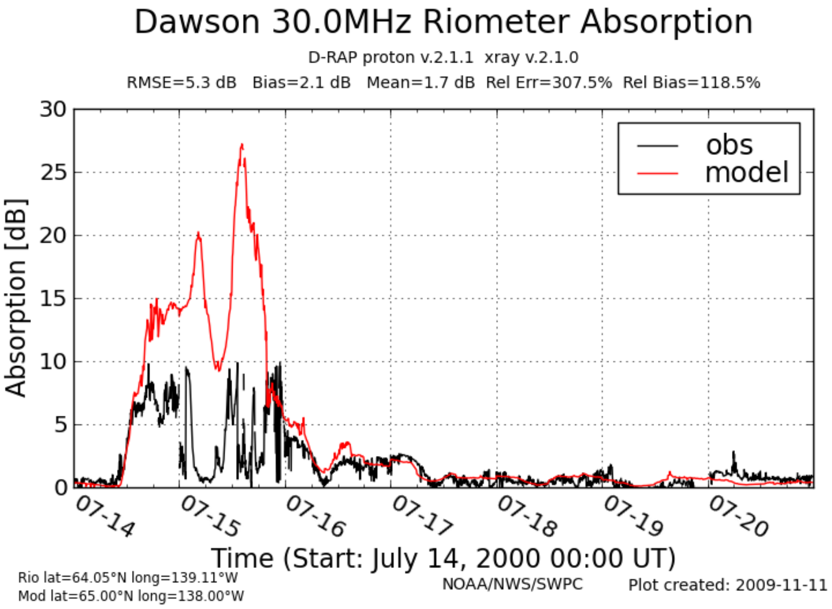

Figure 4. Same as in Fig. 2 but at Dawson.

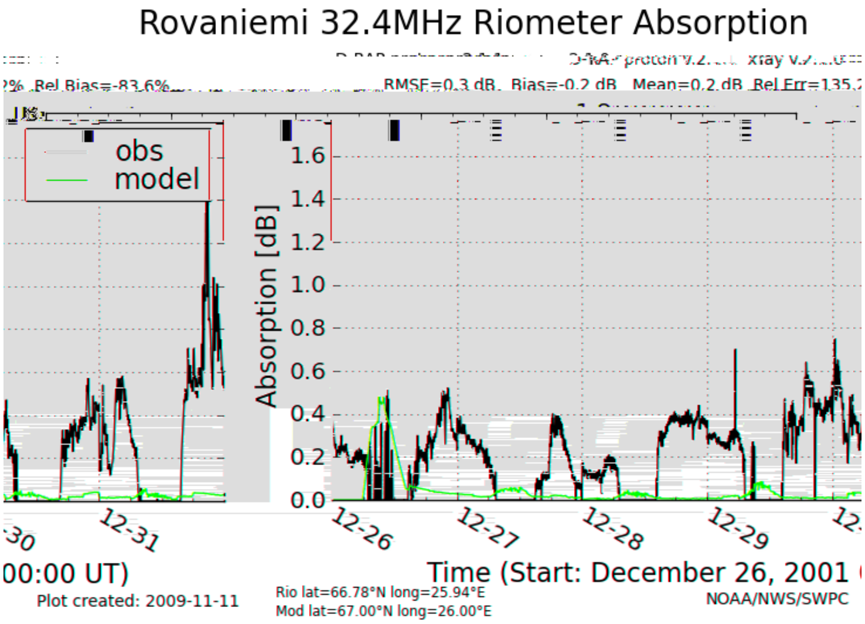

Figure 5. Comparison of model and riometer absorption at Rovaniemi for period 10.

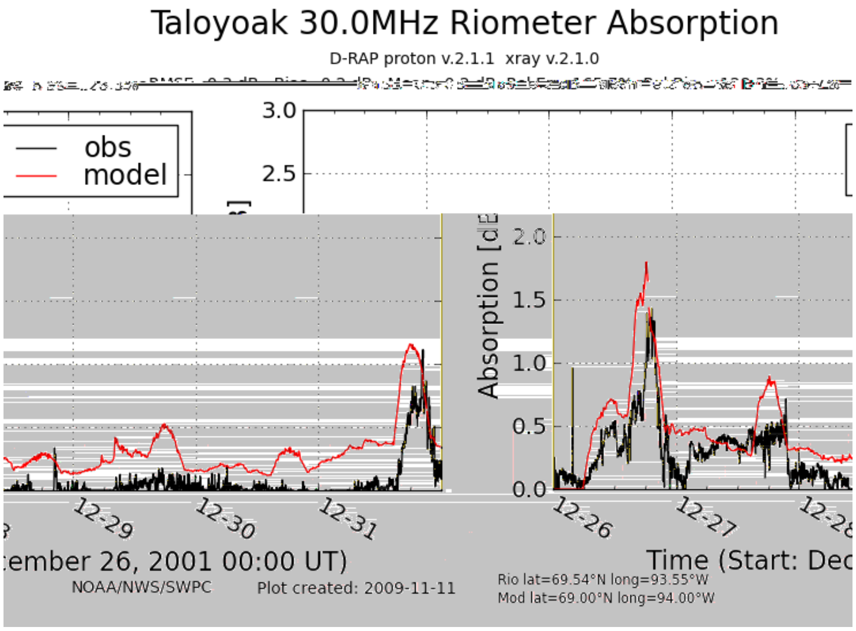

Figure 6. Same as in Fig. 5 but at Taloyoak.

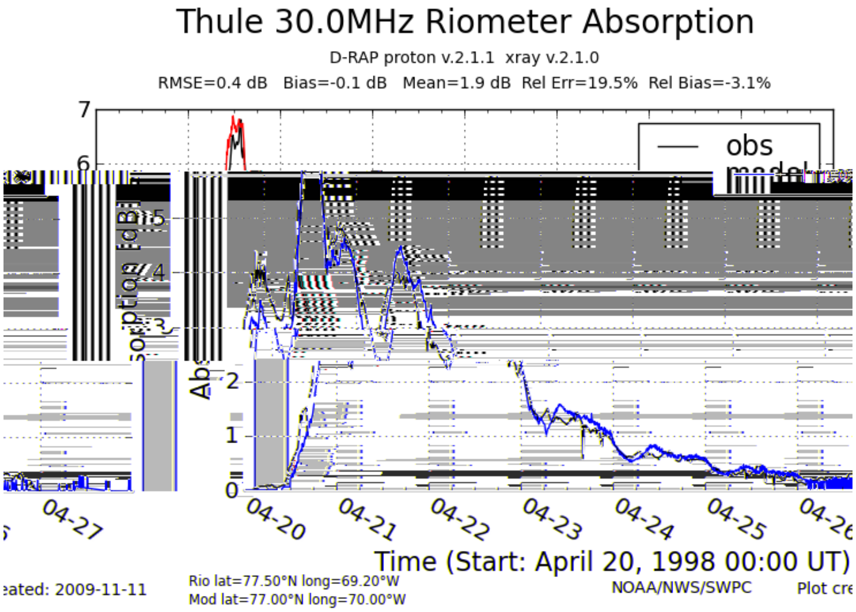

Figure 7. Comparison of model and riometer absorption at Thule for period 1.

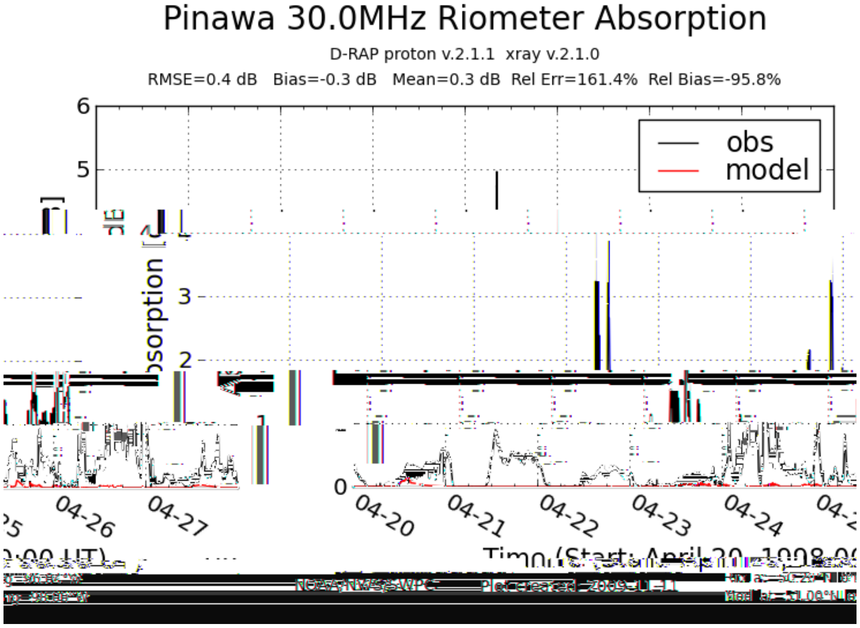

Figure 8. Same as in Fig. 7 but at Pinawa. The increased absorption after April 24 is tentatively associated with contribution by the auroral particle precipitation.

Summary

In summary, with the addition of the PCA model by Sauer and Wilkinson (2008), the new operational global D-RAP model provides a substantially upgraded new product to SWPC customers compared to the previous version, which only accounted for the ionospheric D-region absorption due to X-ray flare events. This in particular applies to such customers as airlines currently mandated to use HF communications on cross-polar routes poleward of about 82° latitude. As already shown by Sauer and Wilkinson (2008), on average the model performs reasonably well compared to a riometer station located inside the auroral oval, such as Thule (e.g., Table 3 and Figs. 1 and 7). In general, however, the model output should be treated as a *qualitative indicator* of highly perturbed conditions. The following areas may need to be addressed in the future both in terms of further model development and model validation:

- Because the SEP component of absorption is much larger at the locations considered, it has been impossible to isolate and validate the X-ray component of the operational model within the present validation effort.
- The validation comparisons have been performed at typical riometer frequencies of about 30 MHz. At typical HF frequencies used for communications the absorption values and absolute model errors and biases may be expected to be much higher. Within this project, it was impossible to validate the frequency conversion relation (1), which would require measuring absorption at two or more frequencies at the same location and under the same conditions.
- The validity of one of the D-RAP products, an estimated recovery time after an event, has not been addressed by the present project.
- At high-latitude stations in the American sector, including Thule, the model occasionally overestimates the peak ionospheric absorption by more than a factor of 2.

- In the European sector the model appears to systematically underestimate the absorption.
- Additionally, the model does not account for a potentially substantial contribution to the total absorption due to auroral particle precipitation at high- and mid-latitudes.
- Given generally very large relative errors of absorption estimated by the model, the errors of the highest affected frequency displayed on the operational product's web page (±2 MHz) appear highly unrealistic and misleading and should be removed.

Recommendations

Based on the results presented in this report, this section offers recommendations for future validation studies and possible improvements of the scientific models. Additional material such as time series and scatter plots not presented here are available from SWPC by request.

Future validation effort

- A separate study should be conducted in order to affirmatively validate the X-ray component model on well isolated X-ray flare events on data from more midlatitude riometer stations or other data sources at lower latitudes.
- As more riometer station data become available in or close to real time, the feasibility of real-time "on-the-fly" verification should be considered for implementation in future versions of the model.
- An expansion of the present effort to other longitude sectors and to the Southern Hemisphere should be considered.

Scientific model improvements

- Based on the results of this and future validation studies, the PCA model of Sauer and Wilkinson (2008) should be considered for further improvement perhaps by a more accurate treatment of the SEP energy spectrum and the geomagnetic energy cutoff at subauroral latitudes.
- An R&D effort to develop a parameterization for the auroral absorption should be initiated at SWPC or in a wider space-weather research community.

Reference

Sauer, H. H., and D. C. Wilkinson, Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons, Space Weather, 6, S12002, 2008.