EDGES MEMO #143

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS 01886
June 2, 2014

Telephone: 781-981-5400
Fax: 781-981-0590

To: EDGES Group

From: Alan E.E. Rogers

Subject: Weighted electron temperature in ionosphere from EDGES-2 data.

Introduction

Single frequency radiometers operating in the range of 18 to 40 MHz, known as riometers, are used to measure the attenuation of the ionosphere relative to some minimum level observed over a period of a year or more. The information is inferred from the decrease in total power from the Galactic foreground which is a repeatable function of local sidereal time (LST) provided the radiometer is calibrated well enough to remove instrumental drifts with time. The attenuation through the ionosphere can be used to obtain the product of the electron concentration and collision rate integrated along lines of sight to the antenna. The emission from the ionosphere in the 18 to 40 MHz range is normally much smaller than the absorption and consequently little information is obtained on the temperature of the electrons. The emission is relatively more significant in the 100 to 200 MHz and can be separated from the attenuation by observing a change in the broadband spectrum at a given LST since the spectral shape depends on both the absorption and emission according to the equation radiative transfer. For a uniform medium

$$T_a = T_g e^{-\tau} + T_e \left(1 - e^{-\tau}\right)$$

where T_a = observed "antenna temperature

T_g = foreground brightness temperature

T_e = electron temperature

τ = opacity

The EDGES-2 system at the MRO shows excellent repeatability of the calibrated spectra from different days at the same sidereal time. Upon closer examination there are small changes which are well fit by changes in the ionosphere. While it is not yet possible to obtain traditional riometric measurements, since to date insufficient EDGES-2 data has been acquired to obtain reference values of the foreground with minimal ionosphere for the full 24 hour range of LST, accurate measurements can be made of changes in the ionosphere along with the electron temperature of the region where the change occurs.

If a change is made in the ionospheric opacity (see memo 79) the change in the spectrum is approximately

$$\Delta T(f) = \left(-T_g f^{-2+s} + T_e f^{-2}\right)\Delta\tau$$

where ΔT = change in spectrum (K)

$\Delta\tau$ = change in opacity at 150 MHz

T_g = Sky temperature at 150 MHz from EDGES data

T_e = weighted electron temperature at 150 MHz.

s = spectral index of sky at 150 MHz from EDGES data

f = frequency normalized at 150 MHz

The frequency dependence of ΔT allows the estimation of the weighted electron temperature for any value of $\Delta\tau$ since the spectral index, s, is known. Figure 1 shows an example of spectra of ΔT for different days at the same sidereal time along with the fits and the values of ΔT and T_e. The spectrum of ΔT are derived from the difference of the spectrum for a given day and the average of all days. The weighting depends on the product of the magnitude of day to day fluctuation and the attenuation at the altitude where the fluctuation in attenuation occurs.

Care is needed in the fitting process to minimize the effect of bias. The value of T_e is obtained from a weighted least squares fit to the functions af^{-2+s} and b^{-2} to obtain

$$-T_g\Delta\tau = a$$

and $-T_e\Delta\tau = b$

so that $\Delta\tau = a/T_g$

and $T_e = b/\Delta\tau = -(b/a)T_g$

In this case while a and b are the maximum likelihood values the value of T_e can be biased since it is derived from the ratio.

A method for removing the bias is to avoid the division by taking the product

$$T_e\overline{a^2} = -\overline{ab}\,T_g$$

And in this case the bias can be removed from $\overline{a^2}$ and $\overline{ab}$ by subtracting the noise

$$\overline{a^2}' = \left\langle a^2 - 2\,C_{aa}\,rms^2\right\rangle$$

$$\overline{ab}' = \left\langle ab - 2\,C_{ab}\,rms^2\right\rangle$$

Where C_{aa} and C_{ab} are the values from the covariance matrix and rms is the rms residual from the fit used to obtain the values of *a* and *b*. This method is similar to the method of bias removal used for the incoherent averaging of interferometer correlation amplitudes discussed in Rogers, Doeleman and Moran 1995.

A sequence of 16 days of EDGES-2 data from day 108 to 126 (excluding days 109, 115, 125) was analyzed in one hour integrations at the same sidereal time each day. The 16 days provide 120 independent difference spectra. The averaging of the noise corrected values of a^2 and ab for 120 differences improves the SNR by $120^{1/4}$. An alternate procedure of taking the difference of the spectrum for each day from the average is approximately equivalent but requires multiple iterations to obtain a clean average if the spectra from one or more days has been corrupted by RFI or solar flares. In the case of using all the possible difference spectrum those different spectra with corruption can be individually discarded based on setting of a threshold for the rms. Tests show that setting a limit below 1 K is needed to adequately reject changes in solar flux. The typical signature for a change in the solar flux has a positive spectral index, thereby allowing an additional check on the presence of effects on the spectra due to the Sun.

Figure 2 shows the magnitude of the fluctuations of ionosphere opacity at 150 MHz as a function of local time for EDGES-2 data from day number 108 through day 126 2014. The behavior is similar to that expected from the variation in electron density of Rishbeth and Mendillo 2001 with a rapid rise at sunrise, peak at midday and a decline to a low level at midnight.

Figure 3 shows the weighted electron temperature from the same data. The results are variable, and have large error bars show no definitive trend with local time. However these results suggest that the fluctuations mostly occur in a region with electron temperature below 1000 K and above 300 K consistent with the irregularities being in the F layer above the D and E layers.

A test of the time scale of the perturbations was made by reducing the integration time of each spectrum to 12 minutes and observing that the correlation for a specific difference spectrum persists for about 30 minutes to an hour. It is also noted that the strength of the variations are reduced integrations longer than about 30 minutes. This time scale is consistent with the gravity wave perturbations of the electron density reported by Nicolls et al. Further work is in progress.

References:

Nicolls, M. J., Vadas, S. L., Aponte, N., & Sulzer, M. P. (2014) Horizontal parameters of daytime thermospheric gravity waves and E region neutral winds over Puerto Rico, *JGRA*, **119**, 575-600. http://adsabs.harvard.edu/abs/2014JGRA..119..575N

Risbeth, H. and Mendillo, M., (2001) Patterns of F2 layer variability, *Journal of Atmospheric and Solar-Terrestrial Physics*, **63**, 15 pp. 1661-1680.

Rogers, A. E. E., Doeleman, S. S., & Moran, J. M. (1995) Fringe detection methods for very long baseline arrays, *AJ*, **109**, 1391-1401. http://adsabs.harvard.edu/abs/1995AJ....109.1391R

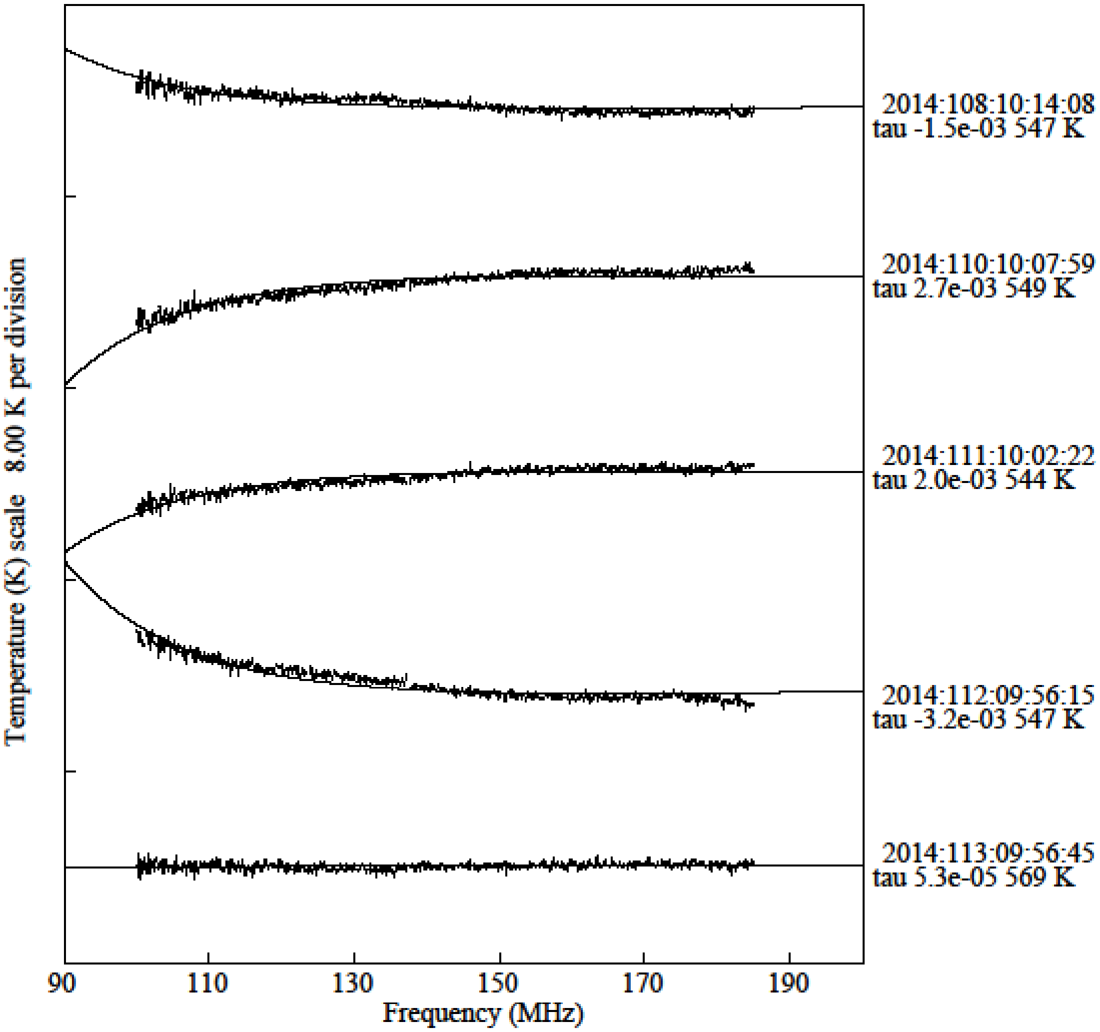

Figure 1 Spectra from days 108, 110, 111, 112 and 113 at the Galactic hour angle of 14 hours after subtraction of the average. An integration of 1 hour was used with some data lost due to RFI excision and exclusion. The values of opacity are the difference from the average for all days. An opacity value on day 111 is 2×10^{-3} referred to 150 MHz which corresponds to about 0.6 dB at 18 MHz.

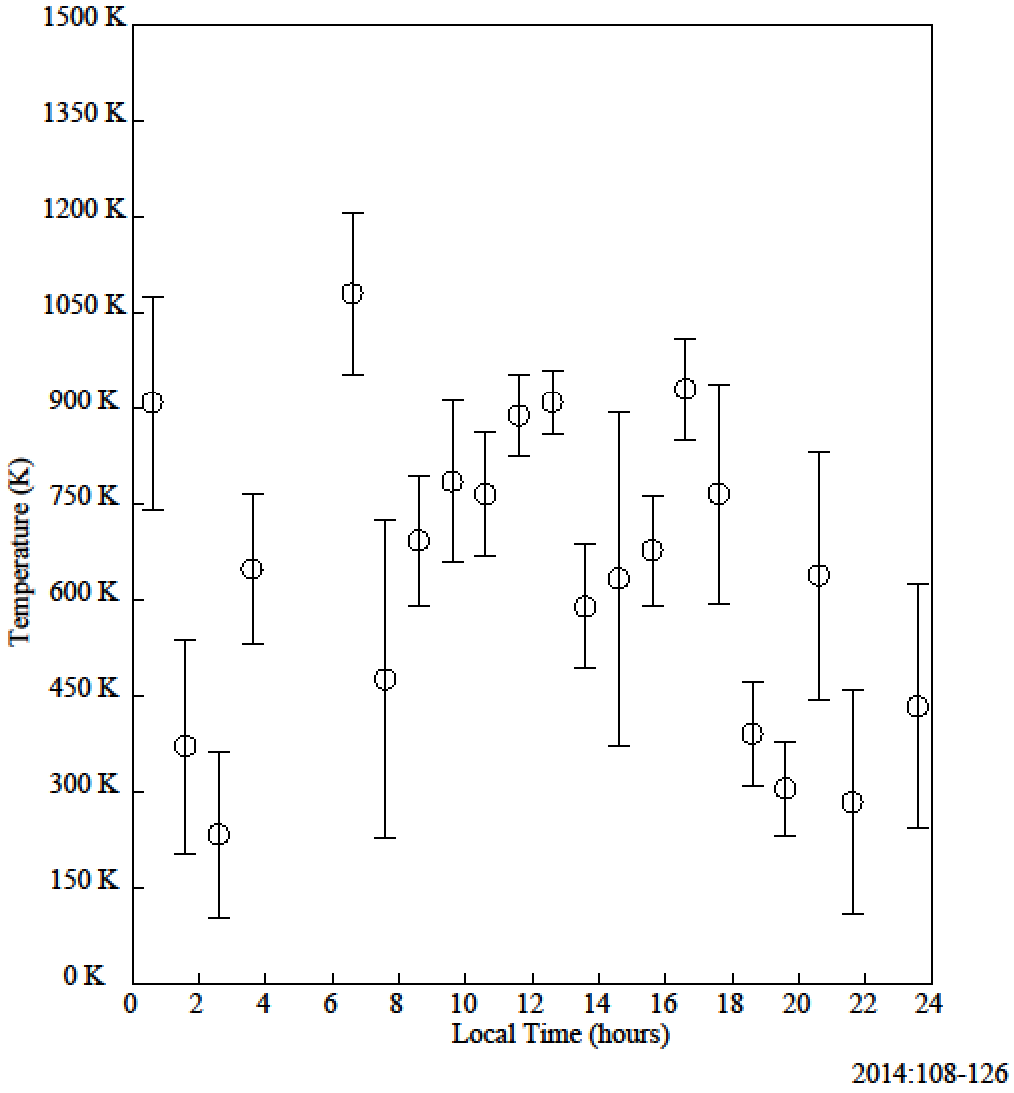

Figure 2. Magnitude of change of opacity in ionosphere due to day to day differences which result from irregularities.

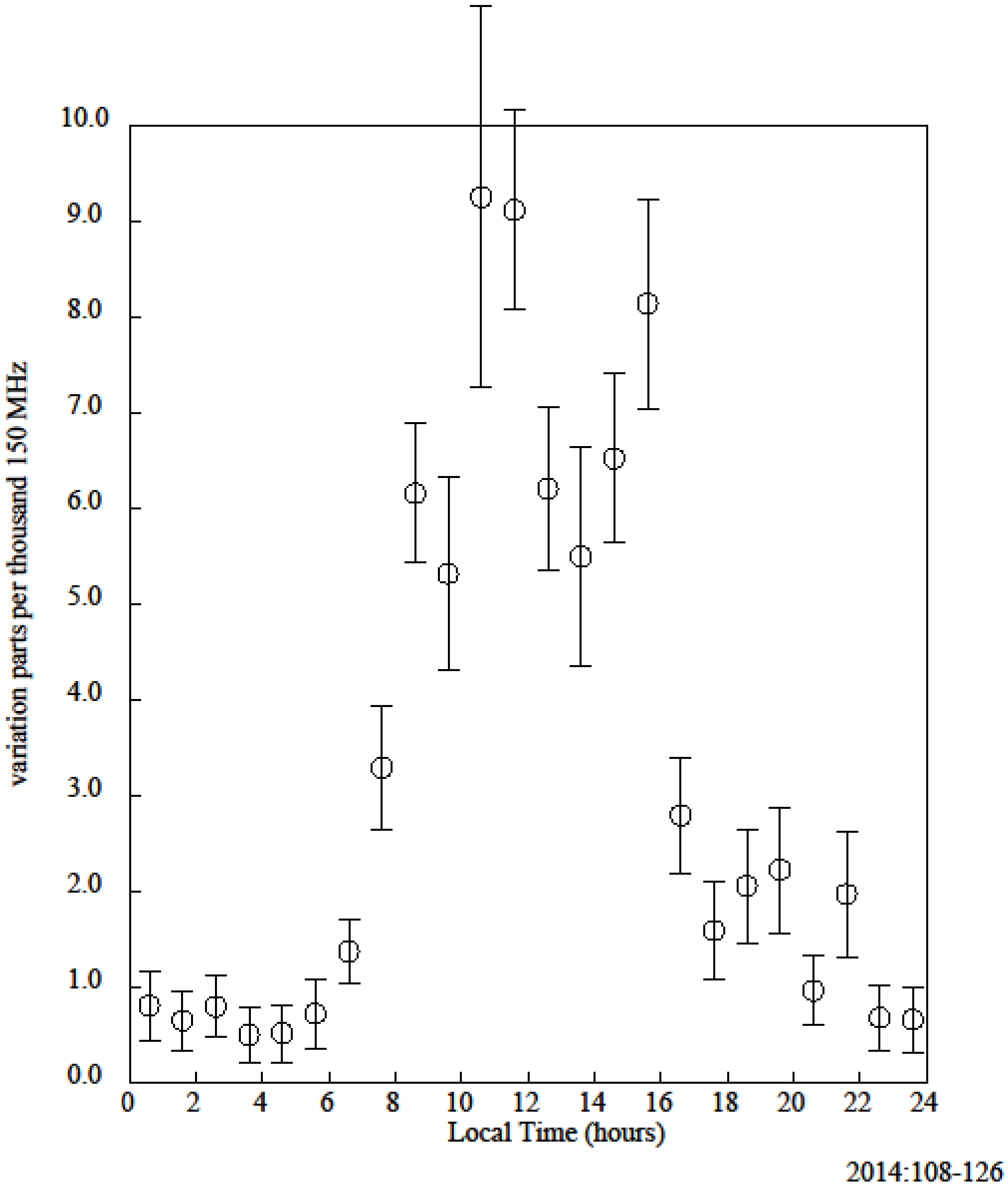

Figure 3. Electron temperature in the ionosphere weighted by the product of the opacity and attitude of irregularities.