D-REGION ELECTRON DENSITIES DURING SOLAR FLARES FROM VLF RADIO MEASUREMENTS

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ABSTRACT

Simultaneous VLF phase and amplitude measurements made over long, mainly ocean paths, are used to determine the enhancements in ionospheric D-region electron densities as a function of solar X-ray flux (measured on the GOES satellites) during a wide variety of solar flares ranging from solar minimum through to (the current) solar maximum. For example, on a typical long ocean path near solar maximum, an X2 flare was found to lower the effective (Wait) reflection height, *H'*, from about 71 km down to 60 km and to increase the (Wait) sharpness factor, β, to about 0.525 km^{-1}.

INTRODUCTION

VLF radio monitoring of the D-region has the advantage that it can be done continuously; this is very desirable given that our current ability to predict the precise timing of solar flares is rather poor. Although rocket borne probes can potentially give greater detail in electron density versus height profiles, the difficulties associated with matching their timing with solar flares are very considerable. Higher frequencies, such as those used with ground-based incoherent scatter radars can also generally give better ionospheric height details but the amount of reflection from (lower) D-region heights is usually too small to allow adequate signal to noise ratio.

Fortunately, daytime D-region electron densities can be well described as increasing exponentially with height using the two traditional (Wait) parameters, *H'*, a measure of the D-region height, in km, and β, a measure of the sharpness of the lower edge, in km^{-1}. These parameters have been successfully used with VLF measurements to describe the normal daytime variations in the D-region electron densities [1], [2].

The β and *H'* characterisation has also been used in determining the (greatly) enhanced D-region electron densities during solar flares from VLF amplitude measurements [3], [4]. VLF amplitude changes alone, if made *only* on long paths, cannot generally uniquely determine the values of *H'* and β because the amplitudes on long paths are generally sensitive to both *H'* and β. However, Thomson and Clilverd [3], [4] used a suitable short path (the 600 km path from the 18.3 kHz French transmitter to Cambridge) for which the VLF amplitude was largely independent of β and so the *H'* determined from this path during a flare was able to be used with the VLF amplitude changes measured on a long (ocean) path, during similar sized flares, to obtain the corresponding values of β and hence the electron densities. While this method worked quite well it had some disadvantages: the short path was mainly over land making the modelling less certain, and the flares were not simultaneous because the two available paths were on opposite sides of the Earth.

The method used to obtain the results to be presented here involves the simultaneous measurement of (the changes in) both the phases and the amplitudes of the VLF signals received at Dunedin, New Zealand, after long, mainly sea, paths from (phase) stable transmitters, such as NLK (Seattle, 24.8 kHz), and NPM (Hawaii, 23.4 kHz and 21.4 kHz). The measured flare-induced phase advances and amplitude changes (usually enhancements) are modelled using the NOSC VLF waveguide codes, LWPC and ModeFinder to find the values of *H'* and β which match the measurements. Generally the phase is more sensitive to *H'* and the amplitude is somewhat more sensitive to β. The unperturbed values of *H'* and β (before the flare) have become well known from VLF observations, [1], [2], and corroboration from (comparatively rare) rocket probe measurements such as those of [5]. Given this known (unperturbed) normal base level, it is found that the values of *H'* and β during solar flares can generally be found uniquely from the VLF phase and amplitude values observed during the flare.

Of course, it has been known for many years, eg [6], that solar flares perturb the amplitude and advance the phase of VLF signals. However, only more recently has suitable code (ModeFinder, LWPC) for finding the reflection coefficients and the resulting VLF Earth-ionosphere waveguide modes for given input D-region electron density profiles (eg as values of β and *H'*) become readily available. Also now available are the solar X-ray fluxes measured in the vicinity of the Earth by the GOES satellites. This has enabled the plotting here of β and *H'* as functions of solar X-ray flux, thus characterising the (quite major) D-region electron density enhancements as a function of solar flare power.

VLF PERTURBATIONS

A small solar flare gives rise to only small VLF phase and amplitude changes accompanying the small perturbation in the D-region ionisation; the resulting peak VLF phase or amplitude clearly depends not only on the size of the flare but also on the exact state of the ionosphere before (and during) the flare. For such small flares it is clearly more appropriate to consider the *excess* VLF phase or amplitude as a function of flare power. However, for large solar flares, the resulting D-region ionisation not only completely overwhelms the unperturbed levels but lowers the effective reflection height well below the original level so that the resulting VLF phase and amplitude are likely to depend only on the large flare and to be largely independent of the minor random variations in the D-region just before the flare. For large flares, then, it is more appropriate to consider the total peak VLF phase or amplitude (rather than the perturbation alone) against the flare power. For flares below size C6.3 (see below) the phase/amplitude modelled was that obtained by adding the observed flare phase/amplitude perturbation (from the unperturbed interpolated value on that day) to the mean midday value; for the larger flares the actual observed absolute amplitude was modelled while for the phase perturbations the average unperturbed values on neighbouring days were taken into account to establish the base level.

RESULTS

Using appropriate VLF and GOES data for the year 2000 on the 12.3 Mm transequatorial NLK (Seattle) to Dunedin, NZ, path, the effective height, *H'*, is shown as a function of solar flare power in Fig 1a, where it can be seen that *H'* decreases nearly linearly from around 71 km in unperturbed conditions near midday down to about 60 km for an X2 solar flare; the flare power is given, as usual, as the 0.1 - 0.8 nm solar X-ray flux near the Earth from the NGDC GOES satellite data. (0 dB = 1 μW/m^2 = C1; 10 dB = 10 μW/m^2 = M1; 20 dB = 100 μW/m^2 = X1; 23 dB = 200 μW/m^2 = X2 etc).

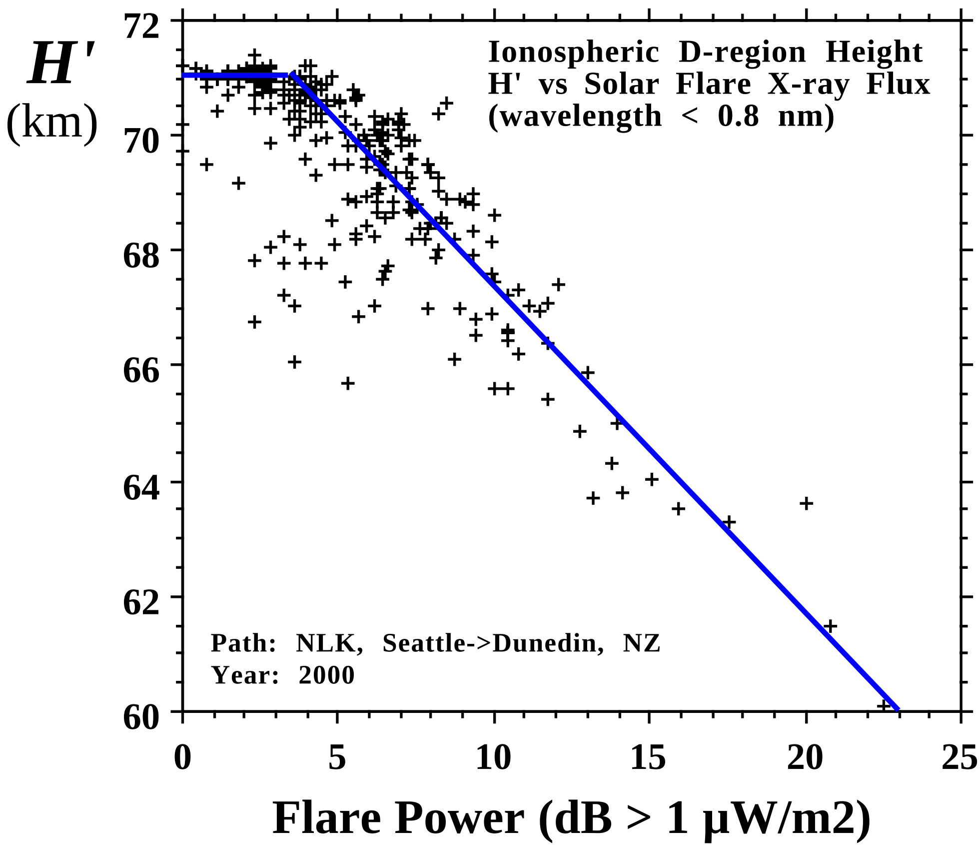


Fig 1a. The D-region height parameter, *H'*, as a function of the solar flare X-ray flux in the band 0.1 - 0.8 nm.

Similarly, the sharpness parameter, β, is shown as a function of solar flare power in Fig 1b where it can be seen that β increases from around 0.42 km^{-1} (for the near midday NLK-Dunedin path) to a general saturation level of about 0.525 km^{-1} (for solar zenith angles up to at least 50^0); this appears to be due to X-ray production swamping the unperturbed production from both solar Lyman-alpha and, in particular, galactic cosmic rays.

For near overhead sun, near solar maximum, the appropriate values of H' and β are 70 km and 0.45 km^{-1} [1].

The (average) unperturbed values of 71 km and 0.42 km^{-1} are used here because unperturbed H' and β vary with (the significant changes in) solar zenith angle [1] along this long (12.3 Mm) path. Also, unperturbed VLF amplitude measurements are indicating that the current solar maximum seems to be giving slightly greater attenuation (and hence slightly lower β) than the previous solar maximum on which the results of [1] were based.

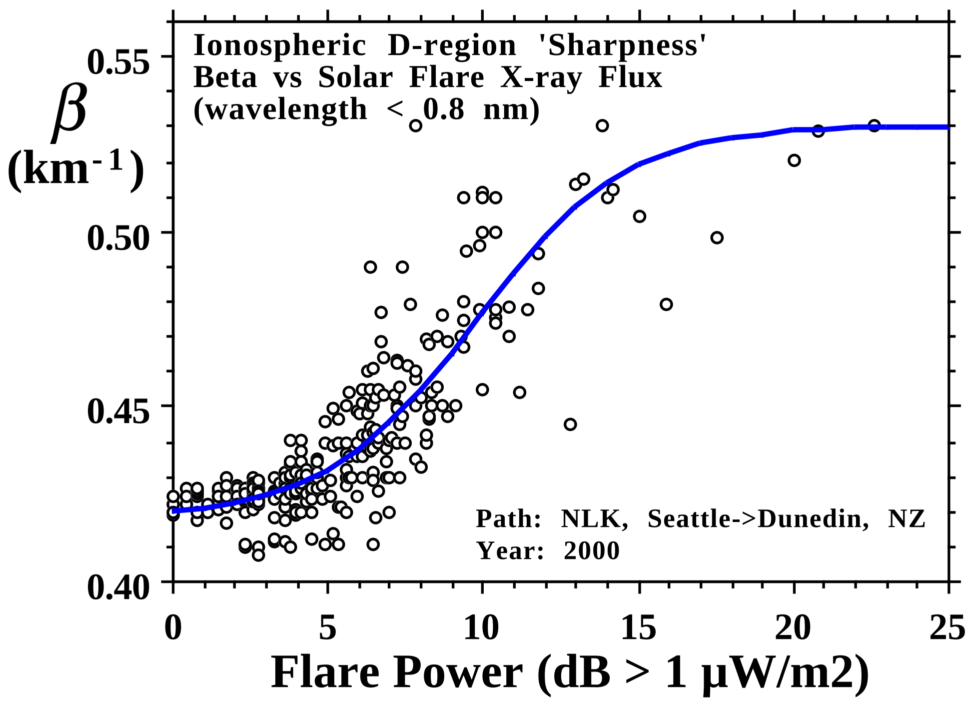


Fig 1b. The D-region sharpness parameter, β, as a function of the solar flare X-ray flux in the band 0.1-0.8 nm.

The electron densities, m^{-3}, are calculated, as a function of altitude, z, in km, by ModeFinder as:

$$N(z) = 1.43 \times 10^{13} \exp(-0.15H') \exp[(\beta - 0.15)(z - H')].$$

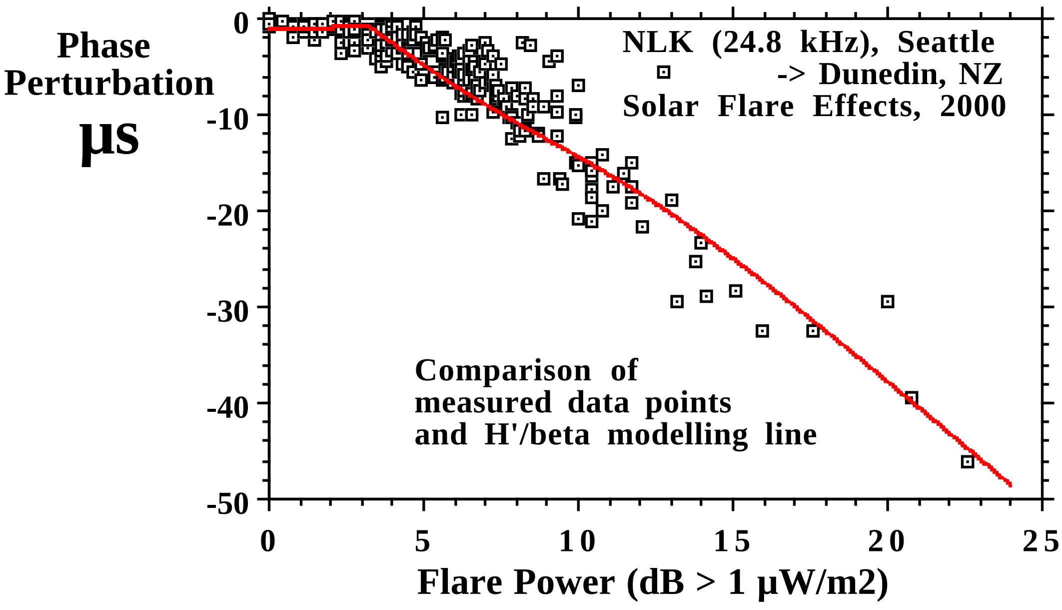
Flare time VLF phases and amplitudes are found to be markedly less sensitive to solar zenith angle than are the normal unperturbed VLF phases and amplitudes.

REVERSE MODELLING

In Fig. 2 are shown the data points of the observed NLK to Dunedin VLF phase and amplitude perturbations as functions of solar flare power. The lines show the perturbations found from calculations with ModeFinder using the flare D-region parameters given in Figs 1a and 1b. The agreement can be seen to be satisfactory.

FURTHER RESULTS

In the Poster presentation, these new flare results from solar maximum will be compared with flare results from earlier in the solar cycle. At times, at solar maximum, the influence of the unperturbed (non-flare) X-ray flux needs to be taken into account, since even in unperturbed conditions, the X-ray flux is a significant contributor to the D-region ionisation, unlike at other times in the solar cycle. The D-region effects of the great X20 flare of 2 April 2001 will be presented; preliminary results indicate these fit the patterns of Figs. 1 & 2 after making the appropriate corrections for the unperturbed (non-flare) X-ray flux (ie the enhanced base level).



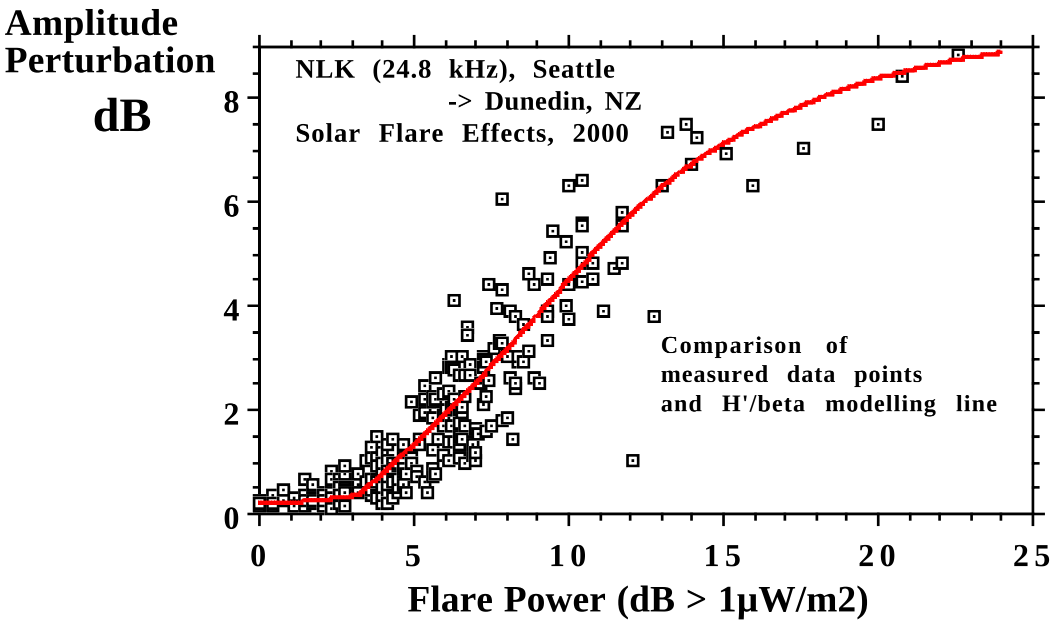


Fig. 2. Modelling test: observed flare time VLF phase and amplitude perturbations (data points) versus calculated values (the solid lines) from ModeFinder using the *H'* and β values in Fig 1.

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[2] W.M. McRae and N.R. Thomson, "VLF phase and amplitude: daytime ionospheric parameters", *J. Atmos. Sol.-Terr. Phys.*, vol. 62(7), 609-618, 2000.

[3] N.R. Thomson and M.A. Clilverd, "VLF radio observations and ionospheric modelling of solar flares", G4.P.3, URSI-GA, Toronto, August, 1999.

[4] N.R. Thomson and M.A. Clilverd, "Solar flare induced ionospheric D-region enhancements from VLF amplitude observations", *J. Atmos. Sol.-Terr. Phys.*, vol. 63 (16): pp. 1729-1737, 2001.

[5] E.A. Mechtly, "Accuracy of rocket measurements of lower ionosphere electron concentrations", *Radio Science*, vol. 9 (3), pp. 373-378, 1974.

[6] A.P. Mitra, *Ionospheric Effects of Solar Flares*, D. Reidel Publishing Company, Dordrecht-Holland, 1974.