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Decay form of the echo amplitude and echo phase of typical early/fast VLF event on 19.8 kHz signal

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Abstract

In this paper, the echo amplitude (M) and echo phase (ϕ) of typical early/fast events on NWC (19.8 kHz) signal received at Suva, Fiji, are modelled to determine their form of recovery (decay). We applied logarithmic and exponential fitting formulas for M and ϕ obtained using a simple theoretical model of VLF wave scattering from lightning-induced electron density perturbations in the lower ionosphere and found that they are highly logarithmic.

Keywords*: Early/fast VLF perturbation, VLF scattering, echo amplitude and echo phase*

1. Introduction

There are two types of short-term perturbations on subionospheric Very Low Frequency (VLF) signals. The first type, discussed by Helliwell *et al*. (1973), termed as "classic or WEP Trimpi" was due to precipitation of energetic electrons into the lower ionosphere near the night-time VLF reflection height (~ 80-90 km) from radiation belts due to whistler-electron interactions. The amplitude and phase perturbations show a delayed and relatively slow onset, corresponding to whistler propagation time plus the duration of the energetic electron travel times. The second type, discovered by Armstrong (1983) is called "early/fast Trimpi" whose onset was too soon (early < 20 ms) after the causative lightning in comparison to classic Trimpi and had comparatively faster recovery time. This class of Trimpi is now commonly referred to as "early/fast" events. The early/fast events are caused by scattering from localised regions of the ionisation enhancements due to the strong lightning producing Transient Luminous Events (TLEs) particularly associated with sprites and in some cases by elves (Inan *et al*., 1995). Dowden *et al*. (1997) from temporal evolution of strong early/fast events from North West Cape NWC-Dunedin path found that the amplitude of the scattered signal decays logarithmically with time, which they suggested to be consistent with the scattering from a bundle of sprite-like conducting columns extending ~ 50 km below the base of the ionosphere due to strong lightnings. Dowden and Rodger (1997) found that early/fast events exhibit logarithmic decay of the scattered amplitude and monotonic decrease of its phase.

The aim of this paper is to present a systematic analysis of recovery or decay of a typical early/fast event on NWC signal observed at Suva (geog. lat.18.2^{o} S, geog. long.178.3^{o} E, L = 1.15). The echo amplitude (*M*) and echo phase (ϕ) of the event on 02 December 2006 at 15:09 hrs UT are modeled to determine whether their recovery or decay is exponential or logarithmic.

2. Experimental Data and Analysis

We use World-Wide Lightning Location Network (WWLLN) VLF system originally set-up for global lightning detection at the University of the South Pacific, Suva, Fiji, to receive radio signals from VLF transmitters. The NWC signal is recorded at 0.1 s intervals using Software based Phase and Amplitude Logger ("SoftPAL"). The Transmitter-Receiver Great Circle Path (TRGCP) distance for NWC-Suva is 7.4 Mm. Five early/fast events selected from the data recorded during 02 – 06 December 2006 were modeled but only one such event is presented here. The events chosen here are those that were observed when entire TRGCP was in dark.

The early/fast events are mainly produced due to narrow angle scattering (Inan *et al*., 1995) and in some cases by wide angle scattering (Dowden *et al*., 1996) caused by ionization enhancements by lightning discharges in the lower ionosphere. Dowden and Adams (1988) using the phasor formalism, designed a model to construct the amplitude and phase of scattered wave from measured signal. This model is used to examine the logarithmic or exponential decay of scattered wave associated with early/fast events observed on the NWC signal.

Figure 1(a) shows the phasor diagram as proposed by Dowden and Adams (1988). To avoid confusion with the directly measured amplitude perturbation (ΔA) and phase perturbation ($\Delta\theta$) of the early/fast events, we use the terms 'echo amplitude' (*M*) and 'scatter or echo phase' (ϕ) to describe the perturbation phasor as suggested by Dowden *et al*. (1997). The main decay of early/fast events measured here is not that of either the amplitude or the phase perturbation, which may be often quite different, but of a vector combination of these as shown in Figure 1(a). Dowden *et al*. (2001) suggested that the magnitude of the phasor of the wave scattered off the sprite plasma when added to the unperturbed phasor of transmission makes the phasor of perturbed wave. Using the phasor diagram in Figure 1(a), the following transformations are obtained:

$$tan\,\phi = \frac{R\,sin\,\Delta\theta}{R\,cos\,\Delta\theta - 1} \quad ,$$

and *M* is given by

$$M = \sqrt{R^2 + 1 - 2R\,cos\,\Delta\theta}\,,$$

where *R* ($R = A/A_0$) is the amplitude of the perturbed wave relative to the unperturbed wave and $\Delta\theta$ ($\Delta\theta = \theta - \theta_o$) is the phase perturbation.

Method of finding ΔA and $\Delta\theta$ for an early/fast event observed on 02 December 2006 at 15:09 hrs UT is shown in Figure 1(b). The fluctuations in the phase and amplitude decay (departures other than random noise) were identified and removed in order to minimize the errors in fitting the curves on logarithmic or exponential scales. Since the

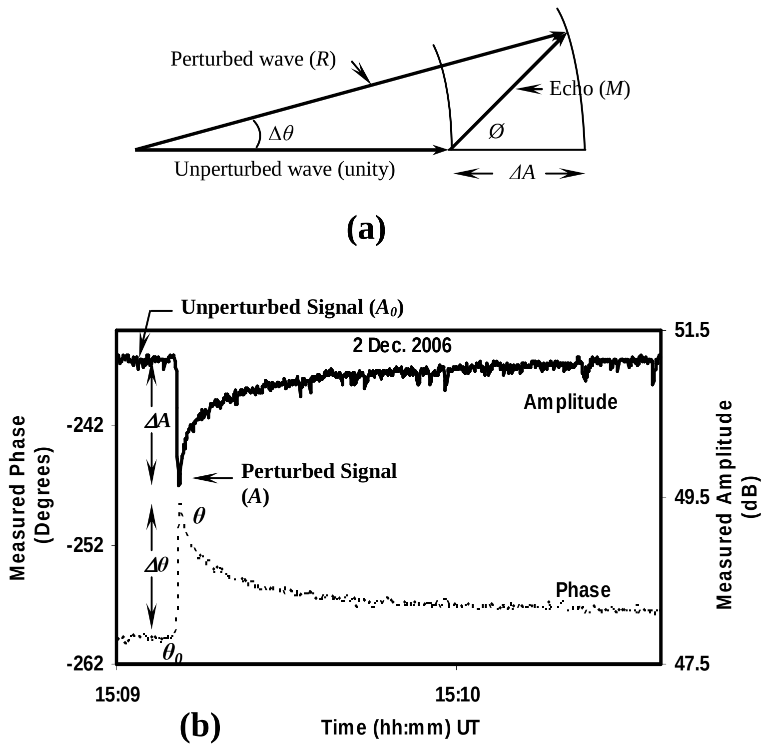

Figure 1. (a) Phasor diagram defining the perturbation phasor ($M\angle\phi$) in terms of the phasors of the perturbed ($R\angle\theta$) and unperturbed ($1\angle 0$) transmission from NWC. The amplitude and phase of all phasors are relative to those of the unperturbed transmission. **(b)** A strong early/fast event on 02 December 2006 at 15:09 hrs UT showing the typical shape of phase (dashed line) and amplitude perturbations (solid line).

amplitude and phase were logged digitally, it was simple to subtract the background signal level and calculate the M and ϕ.

3. Results and Discussion

The general features of early/fast events observed at Suva on the signals from NWC and NPM VLF transmitters have been presented by Kumar *et al*. (2008) which indicated that the early/fast events on both the signals could be observed due to narrow and wide angle scatterings. Most of the early/fast VLF events were associated with absolute amplitude change between 0.2 and 0.8 dB, with a few cases of 1.0 dB. The main aim here is to model the echo amplitude (M) and echo phase (ϕ) referred to as scattered amplitude and scattered phase. The amplitude perturbation (ΔA) and the phase perturbation ($\Delta\theta$) of an early/fast event are also modeled to find out the nature of the recovery of the events. The ΔA in dB and $\Delta\theta$ in degrees are obtained by subtracting the initial or pre-event level amplitude (A_o) and phase (ϕ_o) from the peak of perturbed signal from onset to decay of the event. The variation of ΔA (solid line) and $\Delta\phi$ (dashed line) is shown in Figure 2 for the event observed on 2 December 2006 at 15:09:58.3 hrs UT (03:09:58.3 hrs LT). Local time of Fiji is given by LT = UT+12 hrs. The length of time spanned is taken as 60s and the early/fast event is set to begin at zero, where the amplitude and phase perturbation are at their peaks (onset peaks). As shown in Figure 2 the amplitude perturbation at onset peak is −1.5 dB and the phase perturbation is 11˚. The logarithmic and exponential fit graphs for the ΔA and $\Delta\theta$ during recovery clearly reveal that they are highly logarithmic with time and not exponential. This is consolidated by the large values of the square of correlation coefficients (r^2) for the logarithmic fit curves both for phase (r^2 = 0.9646) and amplitude (r^2 = 0.9646) perturbations. For the amplitude perturbation, the fit was only possible for logarithmic recovery hence the exponential fit is not shown. For the early/fast event shown in Figure 2, the 60 s data during decay were analyzed for the M and ϕ values. The M (solid line) and ϕ (dashed line) values for the first 5 s and for every 20 s from the point of onset are plotted in Figure 3 to find r^2 values for these intervals. For up to first 25 s, the M and ϕ quite reasonably fit the logarithmic time decay as indicated by the high values of r^2 (0.97-0.98 for M and 0.87-0.92 for ϕ). However, for the 20-40 s and 40-60 s intervals, the decays poorly fit (very low correlation coefficient) the logarithmic time decays. This indicates that the initial section of about 5-25 s is actually the distinguishing feature of the logarithmic decay. Therefore, for the other early/fast events, the M and ϕ values were calculated only for the first 25 s only. The equation for M is given in the 0-20 s window in Figure 3. M is found to have the form, $M = A \log(t) + B$, where A and B are constants. Since A is negative, $M = 0$ at $t = 10^{-B/A}$. In addition, since M cannot be negative, so the fit cannot be valid beyond this decay time defined by $M = 0$. The r^2 values for M and ϕ are 0.9835 and 0.8793 respectively. For this event, the exponential fit curves for M and ϕ were also plotted. It was found that M had r^2 value of 0.7921 while the exponential fit for ϕ was

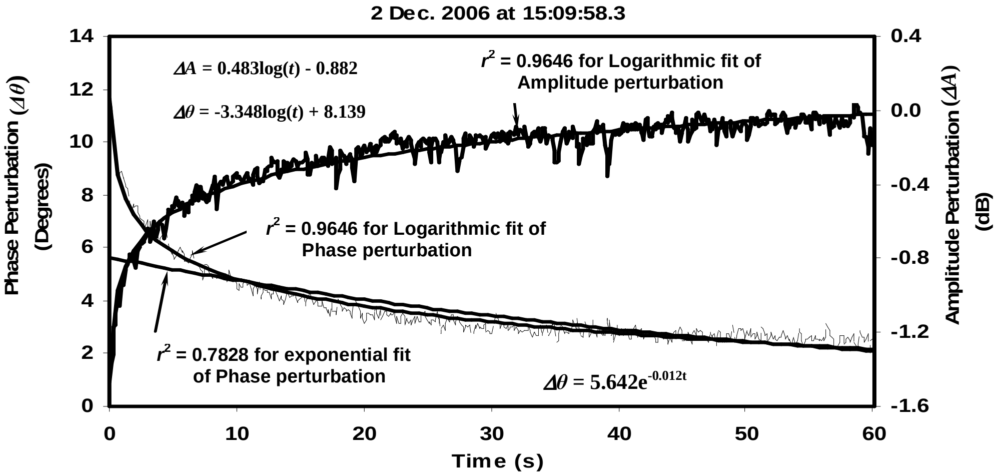

Figure 2. Amplitude (solid line) and phase (dashed line) perturbations associated with an early/fast event on 2 December 2006 at 15.09.58.3 hrs UT. The exponential and logarithmic fittings are shown both for the amplitude and phase perturbations along with the fitting equations and the square of correlation coefficients (r^2).

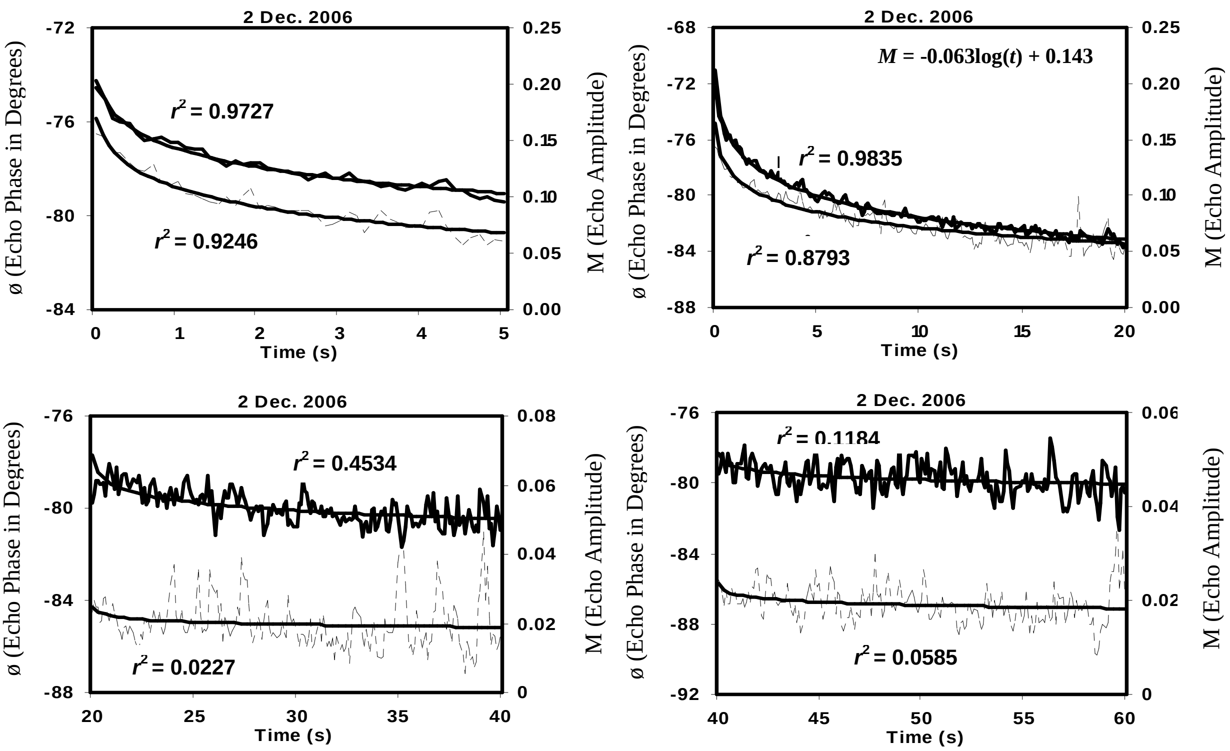

Figure 3. The plots of echo amplitude (M) and echo phase (ϕ) of the scattered wave for the event in Figure 2 for 5s and for 20s durations up to 60s each from the point of onset. The solid and dashed traces represent M and ϕ respectively.

not possible. The r^2 values for logarithmic fit of the five events were found to be between 0.81-0.98 for M and 0.50-0.99 for ϕ. It was found out that r^2 values for exponential fit curves were poor when compared to the logarithmic fit curves.

The decay of the echo amplitude and phase could be explained in terms of scattering from bundles of conducting columns of sprite plasma. Dowden *et al.* (1997) suggested that such conducting columns formed by lighting discharges associated with TLEs probably sprites would decay several hundred times faster at the bottom end (around 40 km altitude) than at the top (~90 km). Since the plasma at any altitude decays exponentially in time with the time constants increasing exponentially with altitudes, the altitude of the effective bottom of the columns would decrease logarithmically with time. The VLF waves will see the exponential decrease in plasma density of conducting column and logarithmic decrease in the length of column. Both may affect the scattered amplitude and phase as a result both the types of fittings are possible. The better values of correlation coefficients with logarithmic fitting indicate that the decreased length of conducting column contributes more significantly to the scattering of the amplitude. Dowden and Rodger (1997) suggested that the similarity of the VLF amplitude and phase perturbations of events clearly identified with red sprites (Dowden *et al*., 1996) and the logarithmic decay of echo amplitude and phase implies a tall but laterally structured plasma body as the cause of scattering of the VLF signals.

4. Conclusions

The amplitude of the perturbation phasor (echo amplitude) of typical early/fast event observed on the NWC signal decays logarithmically with time for initial 20-25 s from the onset. Although the amplitude or phase perturbations may be apparent even 100s of the onset but significant amount of decay occurs in the first 5s which tends to be monotonic after 20-25 s. It is this duration which mainly determines the decay to be logarithmic. For M, initial period ($t \leq 25$ s) could be best described by the logarithmic fit. The tail ($t > 25$ s) gives poor correlation coefficient value with logarithmic fit and shows decay to be monotonic. VLF scattering from conducting columns associated with TLEs probably sprites in which the plasma at any altitude decays exponentially in time with time constants increasing exponentially with altitude and the length of columns decreasing logarithmically seems to be the mechanism responsible for the above form of recovery of early/fast events observed on NWC signal at Suva.

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