Subionospheric early VLF perturbations observed at Suva: VLF detection of red sprites in the day?

Sushil Kumar[a], Abhikesh Kumar[a], Craig J. Rodger[b]

[a] School of Engineering and Physics, The University of the South Pacific, Suva, Fiji.

[b] Department of Physics, University of Otago, Dunedin, New Zealand.

Abstract

First observations of early VLF perturbations on signals from NWC (19.8 kHz) and NPM (21.4 kHz) monitored at Suva, in the month of November 2006, are presented. The early/fast, early/slow, early/short (RORD), and step-like early VLF perturbations are observed on signals from both the transmitters. The early/fast VLF events are found to occur more often in the nighttime than in the daytime whereas step-like early events predominantly occur in the daytime. Most of the early VLF events are associated with amplitude changes between 0.2-0.8 dB with only a few cases > 0.8 dB. In general, the recovery time of daytime early/fast VLF events is less when compared to the nighttime early/fast VLF events. The lightning location data provided by the World-Wide Lightning Location Network and broadband VLF data recorded at Suva have been analysed to identify the location of causative lighting discharges along the great circle paths between transmitter and around the receiver, and the sferics associated with causative lightning of early VLF events. This research is the first to report both daytime early/fast VLF perturbations with faster recovery and also step-like early VLF perturbations initiated and ended by the lightnings which are most likely associated with red sprites and/or elves occurring in the day-time.

* Author for correspondence: Sushil Kumar, kumar_su@usp.ac.fj, Fax: 00679-3590016

1. Introduction

The Very Low Frequency (VLF) radio signals generated by navigational transmitters and lightning discharges propagate by multiple reflections in the waveguide bounded by the Earth's surface and the lower region of the ionosphere. The measurements of amplitude and phase of the VLF transmission provide information on the long and short time scale variations of VLF signal strength and hence on the D-region of the ionosphere. The short time-scale (~100 s) VLF amplitude and/or phase perturbations, so-called Trimpi, were first recognized by M. L. Trimpi in the VLF data recorded in Antarctica and have been discussed by *Helliwell et al*. [1973]. *Helliwell et al*. related such Trimpis (now termed "classic or WEP Trimpi") to the precipitation of energetic electrons into the lower ionosphere near the nighttime VLF reflection heights (~ 80-90 km) from radiation belts due to whistler-electron interactions. The onset time delay of classic Trimpi (~1s) was related to the time of whistler sferic propagation, interaction with electrons in the radiation belt, and electron precipitation, while their slow decay (~100s) was related to the slower charge density relaxation in the ionosphere. *Armstrong* [1983] discovered a new type of VLF perturbation whose onset was too soon (early) after the causative lightning in comparison to classic Trimpi and had comparatively faster decay time. This class of Trimpi is now referred as "early" Trimpi [*Inan et al*., 1988] or early VLF perturbation. The early VLF perturbations caused by direct lightning effects on the ionosphere are very common perturbations in active thunderstorm regions, and are caused by scattering from localised regions of the ionisation enhancements in the lower region of the ionosphere due to the strong lightnings producing transient luminous events (TLEs) particularly associated with sprites and elves. The scattering can in some cases shows a narrow-angle due to ionisation enhancements by lightning discharges occurring at distances of about ± 50 km off the transmitter receiver great circle path (TRGCP) [*Inan et al*., 1993; *Inan et al*., 1995; *Inan et al*., 1996a,b], or in other cases show wide-angle scattering including backscatter due to ionisation enhancements by lightning discharges occurring at distances of less than 500 km off the TRCGP and around the receiver [*Dowden et al*., 1996; *Hardman et al*., 1998; *Rodger*, 2003]. The discovery of transient luminous events (TLEs) including optical emissions of red sprites established the mechanisms of direct lighting ionisation enhancements in the lower ionosphere [*Sentman* *et al*., 1995; *Wescott et al*., 1995]. The early VLF perturbations associated with sprites were first reported by *Inan et al*. [1988] from the Trimpi measurements made over United States. It is now believed that sprites in the lower ionosphere have nearly one-to-one correlation with early/fast VLF perturbations [*Dowden et al*., 1996; *Inan et al*., 1996; *Mika et al*., 2005]. *Rodger* [2003] has presented a detailed review on the VLF perturbations associated with lightning discharges. Recently, *Mika et al*. [2006] from the observations taken during EuroSprite2003 have reported the early VLF perturbations associated with elves.

In this paper, we present initial observations of early VLF perturbations on the 19.8 kHz signal from NWC (21.8^{o}S, 114.1^{o}E, 1 MW, L=1.44) and the 21. 4 kHz signal from NPM (21.5^{o}N, 158.1^{o}W, 0.5 MW, L=1.17) communication transmitters observed in Suva (18.1^{o}S, 178.5^{o}E, L=1.16), Fiji, in the month of November 2006. We have used 0.1 s resolution data of amplitude and phase throughout 1-30 November 2006 to study different types of early VLF perturbations both during night and day-times.

2. Experimental Set-up and Data

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 VLF signals from VLF transmitters. The WWLLN system consists of a short (1.5 m) whip antenna, pre-amplifier fixed at the bottom of the whip antenna, and VLF service unit (SU) coupled with pre-amplifier. *Dowden et al*. [2002] have described the details of WWLLN instrumentation and measurement technique of Time of Group Arrival (TOGA) of sferics at multiple sites. SU unit has two parallel outputs and one of the SU outputs is used to record the amplitude and the phase of the VLF signals using Software based Phase and Amplitude Logger (termed a "SoftPAL"). SoftPAL can log phase and amplitude of seven MSK transmitters continuously with time resolutions ranging from 10 ms to 10 s using GPS based timing. The continuous recording of phase and amplitude variations provides the diurnal and short time-scale changes of ionisation properties in the lower ionosphere along the signal paths. The NWC and NPM signals are recorded at 0.1s and are run continuously using Chart for Windows software. The continuous operation is chosen to monitor the diurnal variation in the signal strength and to study night and daytime VLF perturbations. The locations of the transmitters, receiver, and TRGCPs to Fiji are shown in Figure 1. The TRGCP propagation distance is 7.4 Mm for NWC and 5.4 Mm for NPM. A typical example of the diurnal variation of the 1 minute averaged amplitude and phase values for the NWC and NPM signals in decibels and degrees respectively is shown in Figure 2 (a, b), on 21 November 2006. It was geomagnetically a quiet day with maximum three hourly K_p value of 1^{-}. It can be seen from Figure 2 that the rapid changes in phase took place at the time of the amplitude minima and change in phase was in the direction of decreasing phase delay during sunrise and increasing phase delay during sunset. During the time of sunrise and sunset transitions along the transmission path three amplitude minima during sunrise and sunset labelled as SR_1, SR_2, SR_3 and SS_1, SS_2, SS_3 respectively on NWC signal and one minima each during sunrise and sunset on NPM signal, are observed. The NWC signal strength is larger in the nighttime as compared to daytime whereas NPM signal strength is larger in the daytime. There was power dropout for NPM transmitter around 8 and 11 hrs UT which is not a regular occurrence. The local time of Fiji is LT = UT + 12 hrs. Signal minima during the sunrise and sunset transitions observed on long propagation paths are due to the destructive interference of daytime and nighttime modes at the terminator [*Crombie*, 1964; *Clilverd et al*., 1999]. The number of sunset and sunrise minima depends on the distance propagated by signals along the east-west direction or vice-versa.

3. Observational Results

3.1 Overview of Early VLF Perturbations

The TRGCPs of NWC and NPM are in the region of L<1.5 where the electron precipitation causing LEP-produced VLF perturbations (classic Trimpi) is very unlikely. This is supported by the observations of several hundred LEP bursts by the low-altitude S81-1 satellite, with no events occurring below L~1.8 [*Voss et al*., 1998]. Therefore, we consider that all the VLF perturbation events presented here are early VLF perturbation events. The short time-scale perturbations in amplitude and/or phase of the NWC and NPM signals received at Suva clearly reveal the characteristics of early VLF perturbations that include early/fast, early/slow, early/short (RORD) as well as step-like early VLF perturbations, which are reported here for the first time. In the current study we have excluded further consideration of so-called early/short Trimpis or RORDs perturbations, and focus on VLF perturbations with longer time signatures, which are more clearly defined in observations. It is found that early/fast VLF events occur most often in our observations from Suva, early/slow events are very rare, and step-like early events mainly occur in the daytime. Shown in Figure 3 a and b are absolute amplitude changes associated with early VLF events on NWC and NPM signals obtained from the analysis of data in the period of 1-15 November 2006. Most of the early VLF events are associated with absolute amplitude change between 0.2 and 0.8 dB, with a few cases of ≥ 1.0 dB, which is in line with occurrence statistics for early/fast events [e.g. *Moore et al*., 2003; *Mika et al*., 2005].

3.2 Nighttime Early VLF Perturbations

As has been reported previously, early VLF perturbation events occur more frequently at times when entire TRGCP or a part of it is in dark. Indeed, up to now very few VLF perturbations have ever been reported during day time propagation conditions due to the dominance of the Sun as an ionisation source. We present here the typical early VLF events observed when significant portion of TRGCP was in dark up to the location of lightnings associated with early VLF events. Figure 4 (a-f) presents typical early VLF events associated with amplitude increase or decrease and phase advance or retard, observed on the NWC and NPM signals in the nighttime: **a)** on 22 November 2006 at 12:38:33.2 hrs UT on NWC, **b)** on 29 November 2006 at 18:04:10.9 hrs UT on NWC, **c)** on 23 November at 13:02:32.6 hrs UT on NWC, **d)** on 10 November 2006 at 10:48:01.2 hrs UT on NPM, **e)** on 9 November 2006 at 16:06:56.1 hrs UT on NPM, **f)** on 23 November 2006 at 14:02:07.7 hrs UT on NPM. The solid traces (blue) and dotted traces (red) represent the amplitude and phase plots respectively. The vertical dashed lines with arrows in panels (a, b, d) indicate the time of WWLLN-detected lightnings associated with these perturbations. The vertical solid lines with arrows in panels (c, f) indicate the time of radio sferics observed at Suva. In general, the decay rate of early/fast events on NWC signal is faster than the decay rate of such events on NPM signal as can also be seen from this figure. The VLF event presented in panel c is an early/slow event and others are early/fast events. The early/fast events display an instant (fast) onset of about

100 ms followed by the usual recovery of several tens of seconds whereas the early/slow event in panel c shows gradual onset of about 0.5s on amplitude and about 1.1 s on phase. The early/fast and early/slow events are characterised by short (100 ms) and long (0.5-2.5 s) onsets respectively [*Haldoupis et al*., 2004, 2006]. To identify the causative lightning for these early VLF events, we analysed WWLLN data along the TRGCPs near the time of occurrence of perturbations. The WWLLN detects the global lightnings with return stroke currents of more than ~50 kA with spatial and temporal accuracy of roughly 10-20 km and 10 μs respectively and has detection efficiency less than 4%, although a much higher detection efficiency for high peak current lightning [*Rodger et al*., 2006]. The processing centre of WWLLN provides the participating Institutions with monthly data of lightning locations and the stroke times (accurate to μs), on a CD. WWLLN confirms a lightning strike only when 4 or more stations record the same lightning, and at present 28 universities/institutions all over the world are participating in WWLLN. The WWLLN detected a lightning event on 22 November 2006 at 12:38:33.135945 h UT, geog. lat. -21.6418, geog. long. 124.2523 that produced the early/fast VLF event on NWC signal shown in panel a of Figure 4. The location of this lightning has been marked by “1” in Figure 1 which is near the NWC transmitter and within a distance of 50-100 km perpendicular to TRGCP (NWC-Suva). The WWLLN detected a lightning event on 29 November 2006 at 18:04:10.867713 hrs UT, geog. lat. -26.1643, geog. long. 126.1985 which was coincident with the early/fast event on NWC signal shown in panel b of Figure 4. The location of this lightning has been marked by “2” in Figure 1 which is near to the NWC transmitter and within a distance of 300-350 km perpendicular to TRGCP (NWC-Suva). A lightning was detected by WWLLN on 10 November 2006 at 10:48:01.194528 h UT, geog. lat. -13.7828, geog. long. -178.373 coinciding with the early/fast event on NPM signal shown in panel d of Figure 4. The location of this lightning has been marked by “3” in Figure 1 which is near to the receiver and at a perpendicular distance of about 50-100 km from TRGCP (NPM-Suva). The WWLLN did not detect the lightning locations associated with remaining early VLF events shown in Figure 4 (c, e, f), however, radio sferics were observed for VLF events in panels c and f. In general, for about 5% of the total early VLF perturbation events observed at our station, the WWLLN detects the associated lightning with locations along the TRGCP

and around the receiver. This could be due to the low detection efficiency of WWLLN. Using the WWLLN programme installed in the WWLLN PC at our station we can also record the wideband VLF data that can be analysed using *MATLAB* code which gives one spectrogram every second. The wideband VLF data were recorded at our Suva station for 5 minutes at every hour in the nighttime (18-06 hrs LT) during the month of November 2006. The early/slow event on NWC signal shown in panel c occurred during the time of wideband data recording. The analysis of VLF data revealed the sferics on 23 November at 13:02:32.54 hrs UT coincident with the time of occurrence of this early/slow event. Figure 5(a) shows the spectrogram having the sferics (small cluster), coincident with the early/slow event given in Figure 4c. Such sferic cluster is most likely associated with intra-cloud lightning (IC) indicating the possibility of IC lightning activity associated with this early/slow event. At Suva, early/slow events are observed very rarely and in the nighttime only, indicating that not all IC flashes result in early/slow events. The early/fast event on NPM signal shown in panel f of Figure 4 also occurred during the time of wideband data recording. The spectrogram in Figure 5 (b) obtained from wideband VLF data analysis revealed the existence of strong dispersed sferic (tweek) coincident with the early/fast event observed on NPM signal on 23 November at 14:02:07.66 hrs UT. This particular sferic has both ELF and VLF frequency components indicating that most likely positive CG discharges associated with TLE generated it. Strong positive CG discharges with large return stroke peak current that can trigger the red sprites are associated with ELF radio atmospherics observed at large distances (~1500 km) from the discharge [*Sukhorukov and Stubbe*, 1997; *Cummer and Inan*, 1997; *Ohkubo et al*., 2005]. The propagation of ELF energy below cutoff frequency (~ 1.8 kHz) of first order mode of tweek as shown in the spectrogram must occur by quasi-transverse electromagnetic mode waves since other modes at these frequencies will be evanescent. The distance, *d*, travelled by the tweek in the earth-ionosphere waveguide, calculated using the method used by *Kumar et al*. [1994] is found to be 1400 km. Tweeks propagate by multiple reflections in the earth-ionosphere waveguide. Since the number of reflections and direction of arrival of sferics can not be estimated, the exact location of lighting is not known. However, from the propagation distance it can be said that lightning discharge associated with this tweek occurred within the TRGCP range.

3.3 Daytime Early VLF Perturbations

The occurrence rate of early VLF perturbations on both the NWC and NPM signals when TRGCP is in daylight is considerably smaller as compared to that when TRCGP is in dark. We have selected typical early VLF events when significant section of TRGCP was in the daylight. In general, the decay rate/recovery time of daytime early/fast events is faster/less as compared to the nighttime early/fast events. This is expected as the VLF reflection height will be lower during the day, and less of the ionisation change will be significant when contrasted with day-time electron density altitude profiles. However, in some cases recovery is comparable to the night-time early/fast events. This probably indicates the variability in the ionisation changes, relative to the ambient day and night-time electron densities. Figure 6 shows a record of typical early/fast VLF event observed simultaneously on NWC and NPM signals at 06:30:55.8 hrs UT on 21 November 2006. At the time of occurrence of this event the NPM-Suva path was under sunset (modal interference) and the NWC-Suva path under daylight. This event can be regarded as two step early/fast events which may be produced by two strong lightning flashes or by the first and second return strokes of same lightning separated by 50-100 ms or so, each associated with strong electromagnetic pulses (EMP). It can be clearly seen that the recovery of this event is faster as compared to the night-time early/fast events shown in Figure 4. The strong similarities in the onset and recovery signatures of the perturbation events simultaneously on both signals shown in Figure 6 and also with those presented in Figure 4 is strong evidence that these events were also produced by a lightning discharge-generated ionospheric change, implying a TLE occurring during the day and around the receiver. A sample of about 1.5-min record containing three early/fast VLF events observed on 5 November 2006 at 19:53 UT (or 06 November at 07:53 LT) simultaneously on NPM and NWC is presented in Figure 7. At the time of occurrence of these events the NWC-Suva path was under sunrise (approaching modal minimum) and the NPM-Suva path under daytime hence NPM signal strength is more than that of NWC unlike during other events. The time of occurrence of these events is labelled as A, B, C. The events labelled A and B have rather rapid recovery times of about 6 and 15 s respectively. The decay rate for event C is comparatively larger showing the recovery time of about 20s. WWLLN did not detect any lightning within 500 km of the receiver coincident with the perturbations presented in Figures 6 and 7.

Most of the daytime early VLF perturbations are step-like showing fast (step-like) onset, an amplitude change which remains at the perturbed level for about 2 to 4 minutes, and then recovers fast (step-like) similar to the onset. The step-like early events show onset and recovery as step-down and step-up and vice versa. They are observed mostly on the amplitude of either NWC or NPM signals and sometimes on both the signals. They dominantly occur during the daytime propagation conditions and are very rare in the nighttime. No such VLF event was observed in the nighttime during the month of November 2006, on both the signals. The typical examples of step-like early events indicating the onset as step-down and recovery as step-up and for which WWLLN detected the lightnings at start and end are presented in Figures 8 and 9. The step-like early VLF event shown in Figure 8 occurred only on NWC signal on 2 November 2006 at 04:42:13.6 hrs UT and ended at 04:47:00.2 hrs UT. At the time of occurrence of this event NPM-Suva path was under sunset (near modal minimum) and NWC-Suva path under daytime propagation conditions. The WWLLN detected two lightnings on 2 November one at 04:42:13.598046 h UT, geog. gat. -30.7172 and geog. long 147.8907 and another at 04:47:00.118639 h UT, geog. lat. -29.5446, geog. long. 148.0636. The lightnings coincided well with the start and end of VLF event in Figure 8. These locations of lightnings have been marked by “4a” and “4b” in Figure 1 which are at distance of about 500-600 km off the TRGCP of NWC. Figure 9 shows a sample of about one hour amplitude and phase record containing a step-like early VLF events (marked as A and B) in the amplitude of both NWC and NPM signals on 23 November 2006. The event marked by B started at 22:15:43.1 hrs UT which ended at 22:17:55.1 hrs UT. At this time the NWC-Suva path was under daytime propagation conditions whereas NWC-Suva path was tending towards complete daytime propagation after encountering sunrise fadings. Therefore, the amplitude of NWC signal is increasing and the amplitude of NPM signal is almost constant. Phase of NWC signal was not stable during this record. OmniPAL recording of both the signals at Dunedin, New Zealand, for the same duration is shown in lower panel which indicates that at the time of events transmitter power was quite stable. In short-time power off, the amplitude decreases at our site by ~ 40 dB, whereas the change in amplitude associated with these events is about 0.4-0.6 dB which falls very well in the range of change in the amplitudes associated with early VLF events as shown in Figure 3. They are not instrumental or experimental since such events were not seen on other transmitters (not shown here) recorded at the same time. Associated with event (B) only, WWLLN detected two lightnings one at 22:15:42.995315 h UT, geog. lat. -7.9569, geog. long. -174.6567 and another at 22:17:55.0530087 h UT, geog. lat. -11.3159, geog. long. -173.2570, which have been marked by “5a” and 5b” in Figure 1. The locations represented by 5a and 5b are about 50-100 km and 200-250 km respectively off the TRGCP of NPM and about 700-1200 km away from receiver and thus the TRGCP of NWC. It appears unlikely that the lightning with such locations can produce/end the VLF perturbation on NWC signal but detectable perturbations for the sprite related events located well off the GCP, as long as the sprite lies within 500-1000 km of the receiver can be observed [*Rodger*, 1999]. There could be other lightnings in the TRGCP of NWC or near the receiver within 500 km which coincided with these lightnings and produced step-like early perturbations on NWC but were not detected by WWLLN. The other possibility requires the lightning discharge to affect a vast region of the ionosphere, much larger than expected from elves observations of lightning EMP. *Mika et al*. [2006] from the observations of VLF transmission and TLEs during EuroSprite2003 have presented the step-like early VLF perturbations associated with the elves. Theoretical models show that strong EMP associated with elves can lead to the ionisation increase in the lower ionosphere [*Rowland*, 1998]. At elves altitudes this ionisation is expected to last for few minutes [*Rodger et al*., 2001] which can lead to step-like early VLF perturbations. For instance, the doubling of the ionisation at 90 km altitude would take about 30 min to return to 10 % of its ambient value [*Rodger et al*., 2001]. TLEs are expected to occur both during the day and night times. The elves associated ionisation might intrude to daytime VLF reflection heights and lead to step-like early events as presented here.

3.4 Diurnal Variation of Early VLF Events

The diurnal variation of occurrence of early VLF events on NWC and NPM signals for November 2006 is presented in Figure 10 (a, b). For each day, the perturbation events were visually inspected, and a count was made of those that appeared to be early VLF events. Early VLF events occur more frequently between 11-21 hrs UT (23-09 hrs LT) on NWC signal when the TRGCP is completely or partly in the dark. Previously, early VLF events and TLEs have been reported primarily from nighttime observations; our observations include VLF perturbations during time periods when the entire TRGCP is in day-light. During the one month of data examined in this study, roughly 30 % percent of the VLF perturbations on NWC occurred during daytime propagation conditions with the maximum between 02-05 hrs UT and most of which were step-like early VLF events. As noted previously, we are confident that these events are not LEP-produced classic Trimpi, which are very unlikely despite high tropical lightning activity due to increasingly unfavorable gyroresonance conditions [*Friedel and Hughes*, 1992]. The early VLF events on NPM signal also occur more often between 11-20 hrs UT when TRGCP is completely or partly in the dark but overall occurrence is less as compared to that on the NWC signal. This is likely to be due to the larger lightning occurrence rates across Australia when contrasted with the NPM-Fiji cross ocean path.

5. Discussion

5.1 Nighttime Early VLF Perturbations

We have presented the early VLF perturbations (early/fast, early/slow, step-like) observed at a low latitude station and discuss their association with lightnings detected by WWLLN and radio atmospherics observed at the site. The broadband receiver used in this work is also sensitive to sferics from intracloud (IC) lightnings during thunderstorms. The early/fast VLF perturbations on NWC and NPM signals mostly occur when either entire TRGCP or part of it is in dark. The early/fast events are most common sub-ionospheric VLF perturbations caused by direct lightning effects on the lower ionosphere, and are mostly characterised by abrupt onset followed by slower relaxation times for several tens of seconds. *Inan et al*. [1995] first observed the connection between the early/fast VLF events for a small subset of sprites occurring near the TRGCP but at large distances from receiver (>2000 km). They attributed early VLF perturbations to directional (narrow angle) forward scattering from enhanced ionisation due to lightning discharge located ± 50 km off the TRGCP and having lateral extent of ~ 100-150 km. On the other hand, *Dowden et al*. [1996] observed early VLF perturbations in one-to-one relationship with sprites located within ~ 500 km around the receiver and attributed to omni-directional (wide-angle) scattering from sprite generated columns of ionization with shorter scale than the VLF wavelength. The enhancement in the localized conductivity causing early VLF perturbations have been explained by two different processes associated with the direct effect of lightnings: a) heating of lower ionosphere by strong quasi-electrostatic (QE) field generated by strong lightnings causing the conductivity changes [e. g. *Pasko et al*., 1995; *Inan et al*. 1996], and b) extra ionization due to transient luminous events (TLEs), such as sprites and elves [e. g. *Dowden et. al*., 1996; *Moore et al*., 2003; *Rodger*, 2003; *Mika et al*., 2005, 2006]. The mechanism of sustained heating could not be effective for VLF perturbations due to short time scale of the temperature relaxation (< 0.1s) at the altitude larger than 70 km. The early/fast VLF events shown in Figure 4 (a, d) with the locations of causative lightnings within 100 km off TRGCP and marked by "1 and 3 " in Figure 1, indicate that these events were produced by narrow angle forward scattering most likely from sprite enhanced ionisation. Whereas the early/fast event shown in Figure 4b associated with lightning within 350 km of TRGCP marked by 2 in Figure 1 would most likely imply to the wide angle scattering. *Corcuff* [1998] observed early/fast VLF perturbations in the nighttime associated with lightning discharges situated over France at about 350 km distances in perpendicular direction to TRGCP. The early/fast VLF event observed on 29 November on NWC signal shown in Figure 4f with simultaneous occurrence of strong tweek sferic having ELF (<1.8 kHz) frequency components suggests that this sferic may be produced by strong lightning or associated TLEs probably red sprite. About 50% of ELF sferics with slow tail are associated with sprites [*Rodger*, 1999]. However, it is not possible to identify whether ELF part is associated with currents flowing within the body of sprites or with the causative lightning discharge. *Pasko et al*. [1998] have reported that a lightning discharge with larger peak current triggers a sprite within the first millisecond and does not show a separate ELF sferic peak associated with sprites, because the causative lightning and sprite radiate almost simultaneously in time and the electromagnetic radiation in the ELF range produced by sprites could be comparable to that radiated by the causative lightning discharge. The early/slow event observed on 23 November on NWC signal and presented in Figure 4c could be due to CG (not detected) and IC lightnings together. *Johnson and Inan* [2000] were first to report VLF sferic clusters attributed to IC lightning accompanying a cloud-to-ground lightning discharge to be consistently associated with early VLF perturbations. The early/slow VLF perturbations with onset durations of 0.5 to 1.5 s have been reported in association with sprites [*Inan et al*., 1995; *Haldoupis et al*., 2006]. *Ohkubo et al*. [2005] reported an enhanced VLF activity indicative of IC lighting in association with sprites. *Johnson and Inan* [2000] reported that IC lightning associated with sferics generally do not propagate distances larger than 500-800 km, which is not in agreement with WWLLN observations of IC lightning which are detected by multiple receivers many thousands of km away from the discharge location [*Jacobson et al*., 2006; *Rodger et al*., 2006]. *Neubert et al*. [2005] from observations of TLEs during the EuroSprite2003 have reported that the sprites can also be generated by intra-cloud lightnings. *Haldoupis et al*. [2006] have shown that the gradual growth phase of early/slow perturbations is due to complex and dynamic lightning activity, composed of a few CG return strokes and clusters of IC discharges, which produce primary and secondary ionisations respectively. The long onset duration (~ 0.5 s) of early/slow events may be due to secondary ionisation build-up in the upper D-region below the night-time VLF reflection heights produced by EMP fields of successive horizontal IC discharges. It can be said that for this particular early/slow event shown in Figure 4c, the associated sferics seen in Figure 5a can be attributed to the IC lightning activity responsible for secondary ionisation due to EMPs heating. The QE fields from sprite associated CG discharges may have produced the ionisation (primary) in the upper D-region which is less substantial than in case of the early/fast events. Since early/slow events are very rare, the analysis of longer duration of VLF data on several transmitters for early/slow VLF events along with broadband data for radio sferics would be useful to further investigate their slow onset.

5.2 Daytime Early VLF Perturbations: A new phenomena

The observations of sprites and elves are not possible in the daylight using the optical measurements. VLF methods can be used to detect red sprites if optical observations are not possible [*Dowden et al*., 1996; *Hardman et al*., 1998]. A recently identified red sprite signature observed in infra-sound measurements indicate that sprites continue past sunrise into the daytime, supporting our observations [*Farges et al*., 2005]. Since the one-to-one correlation of VLF perturbations and sprites is well established, the VLF sprites can be detected when they occur at perpendicular distance of about 50 km from the TRGCP due to narrow angle scattering [*Inan et al*., 1995] and about 500 km around the receiver due to wide angle scattering and backscattering [*Dowden et al*., 1996]. The sprites can produce significant ionization enhancements (up to many orders of magnitude) with a horizontal scale of ~ 80 km and at altitude of 70-85 km which is the daytime VLF reflection height and where the timescale for relaxation of electron density enhancement is 10-100s [*Glukhov et al*., 1992]. It can be said here that the day-time early/fast VLF events occurring simultaneously both on NWC and NPM signals with recovery times of 5-15s are most likely associated with sprites occurring in the daylight part around the receiver. The similarities in the onset and recovery signatures of early/fast VLF events observed simultaneously on NPM and NWC (Figure 6 and 7) signals are indicative that they were associated with same lightning located around the receiver. The GCPs of NWC and NPM to Suva are such that the simultaneous occurrence of perturbations on these signals would mainly imply wide angle scattering on both transmitter signals or narrow angle on one and wide angle (including backscatter) on the other. There are no reports on daytime early VLF perturbations except on early/short or RORD perturbations observed by *Dowden et al*. [1994], particularly near local noon and not at night. Based on the low occurrence of early/fast events during the daytime as compared to nighttime in the month of November 2006, it can be said that either red sprites occur less often during the day or that the shortest-lived part of the plasma column exists less often below the daytime reflection heights (or some combination of both). Lower recovery times of most of daytime VLF early/fast events compared to nighttime early/fast events indicate the lower time scales for relaxation of electron density enhancements at the daytime VLF reflection heights.

The step-like early VLF events observed in the daylight and as presented in Figures 8 and 9 having the onsets/recovery coinciding with the lightning locations marked by “4(a,b)” and “5(a,b)” in Figure 1 have not been recognised in the literature previously. However they were seen rarely in the nighttime sub-ionospheric VLF data [*Sampath et al*., 2000]. The observations of VLF perturbations associated with lightnings at distances of about 200-600 km perpendicular to the TRGCP seems to be in disagreement with theory of narrow angle forward scattering since it might imply wide-angle scattering or very large spatial areas of affected ionosphere. It is further interesting to note the step-like recovery of these events coincided with lightnings that occurred at a distance of about 200-600 km perpendicular to the TRGCP. Theoretical models indicate that strong lightning EMPs can lead to the changes in the ionisation in the lower ionosphere [*Cho and Rycroft*, 1998] and at elves altitudes near the nighttime VLF reflection heights this ionisation can last for many minutes [*Rodger et al*., 2001]. This would lead to step-like early VLF perturbations having long relaxation times due to long lifetimes of electrons at these altitudes [*Rodger*, 2003]. *Mika et al*. [2006] observed nighttime step-like early VLF perturbations similar to those reported here associated with elves occurring upto the distances of 400 km in perpendicular direction to TRGCP implying the wide angle scattering. *Mika et al*. expressed the possibility of the sprite occurring below the elves and that accounted for wide angle scattering. However, *Mika et al*. did not comment on the step-like recovery of such early perturbations, which can be seen in the data presented in this paper. The observation of step-like early events in the daylight indicates that electron density enhancements associated with elves in some cases may intrude to lower altitudes (~75km) or the sprites occurring at the bottom of elves that cause VLF perturbations. *Rodger et al*. [2001] undertook a simulation study examining the lower ionospheric modification by lightning EMP and have found that both the regions of increases and decreases in the D-region electron density are possible, depending on the relative occurrence of “strong” and “weak” lightning. It is possible that the initial discharge creates an electron density enhancement, which is largely cancelled out by the following discharge, all occurring near the day-time VLF reflection height. Clearly, this is an area for further study, both experimentally and theoretically.

Summary

We have presented recent results on early VLF perturbations observed on NWC and NPM signals during November 2006. Main findings of this study are summarized as follows: **(1)** The lightnings detected by WWLLN that lie within 50-100 and 200-600 km off the TRGCP and occur in simultaneity (just before) of early VLF events may produce narrow and wide angle scatterings of VLF signals. However, it is not possible here to present the statistics on the early VLF events associated with narrow and wide angle scattering since the efficiency of WWLLN is low. **(2)** Simultaneous occurrence of early/fast VLF events on both NWC and NPM signals implies wide angle scattering is common for at least one of the two transmitter signals, with the other signal displaying narrow-angle scattering. **(3)** The wideband VLF data utilized for radio atmospherics associated with lightning discharges producing early VLF perturbations indicates that the sferic (cluster) most likely associated IC discharges contribute to the long duration onset of early/slow VLF event. The single dispersed sferic (tweek) with large amplitude and having ELF components is most likely associated with sprite producing lightning discharge that generates early/fast events. **(4)** Most of the daytime early/fast VLF events have faster recovery rate indicating the faster electron relaxation time of ionization produced by daytime TLEs most likely sprites. The daytime early/fast events seem to have largely escaped from scientific attention since optical observations are not available in the day. **(5)** Step-like early VLF events are reported for the first time. They are found to occur mainly in the daytime. Detection of lightnings by WWLLN at the end of step-like early events and near the location of lightning that initiated these events indicates the possibility of sharp and sufficient decrease in the electron density caused by the comparatively weaker lightning-EMP by increasing the attachment rate without causing significant ionisation responsible for step-like early recovery.

It is now believed that TLEs associated with sprites in the ionosphere have nearly one-to-one correlation with early VLF events [*Haldoupis et al*., 2004; *Dowden et al*., 1996; *Inan et al*., 1996; *Mika et al*., 2005]. VLF methods can be used to detect red sprites if optical observations of sprites are not possible [*Dowden et al*., 1996]. Considering lightnings associated with TLEs occurring around the receiver produce early/fast events on both the signals simultaneously, VLF perturbations as presented here can be used to detect mainly the sprites and elves (at least in some cases) in the absence of optical data in the daytime.

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References

Armstrong, W. C. (1983), Recent advances from studies of the Trimpi effect, *Antarctic J.*, USA, *18*, 281-283.

Cho, M., and M. J. Rycroft (1998), Computer simulation of the electric field structure and optical emission from cloud-top to the ionosphere, *J. Atmos. Sol.-Terr. Phys.*, *60*, 871-888.

Clilverd , M. A., N. R. Thomson, and C. J. Rodger (1999), Sunrise effects on VLF signals propagating over a long north-south path, *Radio Sci.*, *34*, 939-948, 1999.

Corcuff, Y. (1998), VLF signatures of ionospheric perturbations caused by lightning discharges in an underlying and moving thunderstorm, *Geophys. Res. Lett.*, 25, 2385-2388.

Crombie, D. D. (1964), Periodic fading of VLF signals received over long paths during sunrise and sunset, *J. Res. Natl. Bur. Stand. Sect. D.*, *68*, 27-34.

Cummer, S. A., and U. S. Inan (1997), Measurement of charge in sprite-producing lightning using ELF radio atmospherics, *Geophys. Res. Lett.*, *24*, 1731-1734.

Dowden, R. L., C. D. D. Adams, J. B. Brundell, and P. E. Dowden (1994), Rapid onset, rapid decay, (RORD), phase and amplitude perturbations of VLF subionospheric transmissions, *J. Atmos. Terr. Phys.*, *56*, 1513-1527.

Dowden, R. L., J. B. Brundell, W. A. Lyons, and T. E. Nelson (1996), Detection and location of red sprites by VLF scattering of subionospheric transmissions, *Geophys. Res. Lett*, *23*, 1737–1740.

Dowden, R. L., J. B. Brundell, C. J. Rodger (2002), VLF lightning location by time of group arrival (TOGA) at multiple sites. *J. Atmos. Sol.-Terr. Phys.*, *64*, 817-830.

Farges, T., E. Blanc, A. Le Pichon, T. Neubert, and T. H. Allin (2005), Identification of infrasound produced by sprites during the Sprite2003 campaign, *Geophys. Res. Lett.*, *32*, L01813, doi:10.1029/2004GL021212.

Friedel R. H. W., and A. R. W. Hughes (1992), Trimpi events on low latitude paths - an investigation of gyroresonance interactions at low L-values, *J. Atmos. Terr. Phys.*, *54*, 1375-1386.

Glukhov, V., V. Pasko, and U. S. Inan (1992), Relaxation of transient lower ionospheric disturbances caused by lighting-whistler-induced electron precipitation bursts, *J. Geophys. Res.*, *97*, 16,971- 16,979.

Haldoupis, C., T. Neubert, U. S. Inan, A. Mika, T. H. Allen, and R. A. Marshall (2004), Subionospheric early VLF signal perturbation observations in one-to-one association with sprites, *J. Geophys. Res.*, *109*, A110303: doi: 10. 1029/2004JA010651.

Haldoupis, C., R. J. Steiner, A. Mika, S. Shalimov, R. A. Marshall, U. S. Inan, T. Bosinger, and T. Neubert (2006), "Early/slow" event: a new category of VLF perturbations observed in relation with sprites, *J. Geophys. Res.*, *111*, doi:10.1029/2006JA011960.

Hardman, S. F., C. J. Rodger, R. L. Dowden, and J. B. Brundell (1998), Measurements of the VLF scattering pattern of the structured plasma of red sprites, *IEEE Trans. Ant. Propag.*, *40*, 29– 38, 1998.

Helliwell, R. A., J. P. Katsufrakis, and M. L. Trimpi (1973), Whistler-induced amplitude perturbation in VLF propagation, *J. Geophys. Res.*, *78*, 4679-4688.

Jacobson, A.R., R. Holzworth, J. Harlin, R. Dowden, and E. Lay (2006), Performance assessment of the World Wide Lightning Location Network (WWLLN), using the Los Alamos Sferic Array (LASA) as ground truth, *J. Atmos. Oceanic Tech.*, 23, 1082-1092.

Jonhson, M. P., and U. S. Inan (2000), Sferic clusters associated with early/fast VLF events, *Geophys. Res. Lett.*, *27*, 1391-1394.

Inan, U. S., D. C. Shafer, W. Y. Yip, R. E. Orville (1988), Subionospheric VLF signatures of nighttime D-region perturbations in the vicinity of lightning discharges, *J. Geophys. Res.*, *93*, 11455-11472.

Inan, U. S., T. F. Bell, and J. V. Rodriguez (1991), Heating and ionization of the lower ionosphere by lightning, *Geophys. Res. Lett.*, *18*, 705-708.

Inan, U. S., J. V. Rodriguez, and V. P. Idone (1993), VLF signatures of lightning-induced heating and ionisation of the nighttime D-region, *Geophys. Res. Lett.*, *20*, 2355 - 2358, 1993.

Inan, U. S., T. F. Bell, V. P. Pasko, D. D. Sentman, E.M.Wescott, and W. A. Lyons (1995), VLF signatures of ionospheric disturbance associated with sprites, *J. Geophys. Res.*, *22*, 3461-3464.

Inan, U. S., A., Slingeland, V. P. Pasko, and J. V. Rodriguez (1996a), VLF and LF signatures of mesospheric/lower ionospheric response to lightning discharges, *J. Geophys. Res.*, 1*01*, 5219-5238, 1996a.

Inan, U. S., V. P. Pasko, and T. F. Bell (1996b), Sustained heating of the ionosphere above thunderstorms as evidenced in "early/fast" events, *Geophys. Res. Lett.*, *23*, 1067-1070.

Kumar, S., Dixit, S. K., and Gwal, A. K., Propagation of tweek atmospherics in the earth-ionosphere waveguide, *IL Nuovo Cimento*, *17*, 275-281, 1994.

Mika, A., C. Haldoupis, R. A. Marshall, T. Neubert, and U. S. Inan (2005), Subionospheric VLF signatures and their association with sprites observed during *EuroSprite2003*, *J. Atmos. Sol.-Terr. Phys.*, *67*, 1580-1597.

Mika, A., C. Haldoupis, T. Neubert, T. S. Su, R. R. Hsu, R. J. Steiner, and R. A., Marshall (2006), Early VLF perturbations observed in association with elves, *Ann. Geophys.*, *24*, 2179-2189.

Moore, R. C., P. Barrington-Leigh, U. S. Inan, T. F. Bell (2003), Early/fast VLF events produced by electron density changes associated with sprites, *J. Geophys. Res.*, *108*, doi:10.1029/2002JA009816.

Neubert et al. (2005), Co-ordinated observations of transient luminous events during the EuroSprite2003 campaign, *J. Atmos. Sol.-Terr. Phys.*, *67*, 807-820.

Ohkubo, A., H. Fukunishi, Y. Takahashi, T. Adachi (2005), VLF/ELF sferics evidence for in-cloud discharge activity producing sprites, *J. Geophys. Res.*, *32*, Lo4812, doi: 10.1029/2004GL021943.

Pasko, V. P., U. S. Inan, Y. N. Taranenko, and T. F. Bell (1995), Heating, ionisation and upwards discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields, *Geophys. Res. Lett.* , *22*, 365-368, 1995,

Pasko, V. P., U. S. Inan, T. F. Bell, and S. C. Reising (1998), Mechanism of ELF radiation from sprites, *Geophys. Res. Lett.*, *25*, 3493-3496.

Rodger, C. J. (1999), Red sprites, upward lightning, and VLF perturbations, *Rev. Geophys.*, *37*, 317-336.

Rodger, C. J. (2003), Subionospheric VLF perturbations associated with lightning discharges, *J. Atmos. Sol.-Terr. Phys.*, *65*, 591-606.

Rodger, C.J., M. Cho, M. A. Clilverd, and M. J. Rycroft (2001), Lower ionospheric modification by lightning EMP: simulation of the nighttime ionosphere over the United States, *Geophys. Res. Lett.*, *28*, 199-202.

Rodger, C. J., S. W. Werner, J. B. Brundell, N. R. Thomson, E. H. Lay, R. H. Holzworth, and R. L. Dowden (2006), Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study, *Ann. Geophys.*, *24*, 3197-3214.

Rowland, H. L. (1998), Theories and simulations of elves, sprites and blue jets, *J. Atmos. Sol.-Terr. Phys.*, *60*, 831-844, 1998.

Sampath, H. T., U. S. Inan, and M. P. Johnson (2000), Recovery signatures and occurrence properties of lightning-associated subionospheric VLF perturbations, *J. Geophys. Res.*, 1*05*, 183-191.

Sentman, D. D., E. M., Wescott, D. L. Osborne, D. L. Hampton, and M. J., Heavner (1995), Preliminary results from the Sprite94 aircraft campaign, red sprites, *Geophys. Res. Lett.*, *22*, 1205-1208.

Sukhorukov, A. I., and P. Stubbe (1997), On ELF pulses from remote lightnings triggering sprites, *Geophys. Res. Lett.*, *24*, 1639-1642.

Voss, H. D., M. Walt, W. L. Imhof, J. Mobilia, and U. S. Inan (1998), Satellite observations of lightning-induced electron precipitation, *J. Geophys. Res.*, *103*, 11725-11744.

Wescott, E. M., D. D. Sentman, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Preliminary results from the Sprite94 aircraft campaign, blue jets, *Geophys. Res. Lett.*, *22*, 1209-1212.

Figure Captions

Figure 1. The locations of NWC and NPM transmitters, receiver, and great circle paths to Suva. A contour for L = 1.5 is also plotted. The numbers mark the WWLLN-determined locations of the lightnings associated with early VLF perturbations

Figure 2. Typical variation of amplitude and phase of NWC and NPM signals on 21 November 2006.

Figure 3. Change in absolute amplitude of VLF events observed during 1-15 November 2006, **a)** on NWC signal, **b)** on NPM signal.

Figure 4. Typical examples of observed amplitude (solid trace) and phase (dotted trace) perturbations: **a)** early/fast event on 22 Nov. at 12:38:33.2 hrs UT, on NWC, **b)** early/fast event on 29 Nov. at 18:04:10.9 hrs UT, on NWC, **c)** early/slow event on 23 Nov. at 13:02:32.6 hrs UT on NWC, **d)** early/fast event on 10 Nov. at 10:48:01.2 hrs UT on NPM, **e)** early/fast event on 9 Nov. at 16:06:56.1 hrs UT on NPM, **f)** early/fast event on 23 Nov. 2006 at 14:02:07.7 hrs UT on NPM. Dashed vertical lines with arrows in panel a, b, d indicate the time of WWLLN-detected lightning. Solid vertical lines with arrows in panel c and f indicate the time of radio sferics observed at Suva.

Figure 5. Spectrograms showing the sferics observed on 23 Nov. 06 **a)** small sferics cluster at 13:02:32.54 hrs UT coincident with the early/slow event shown in Figure 4c, and **b)** tweek sferic at 14:02:07.65 hrs UT having both ELF and VLF frequency components associated with the early/fast event shown in Figure 4f.

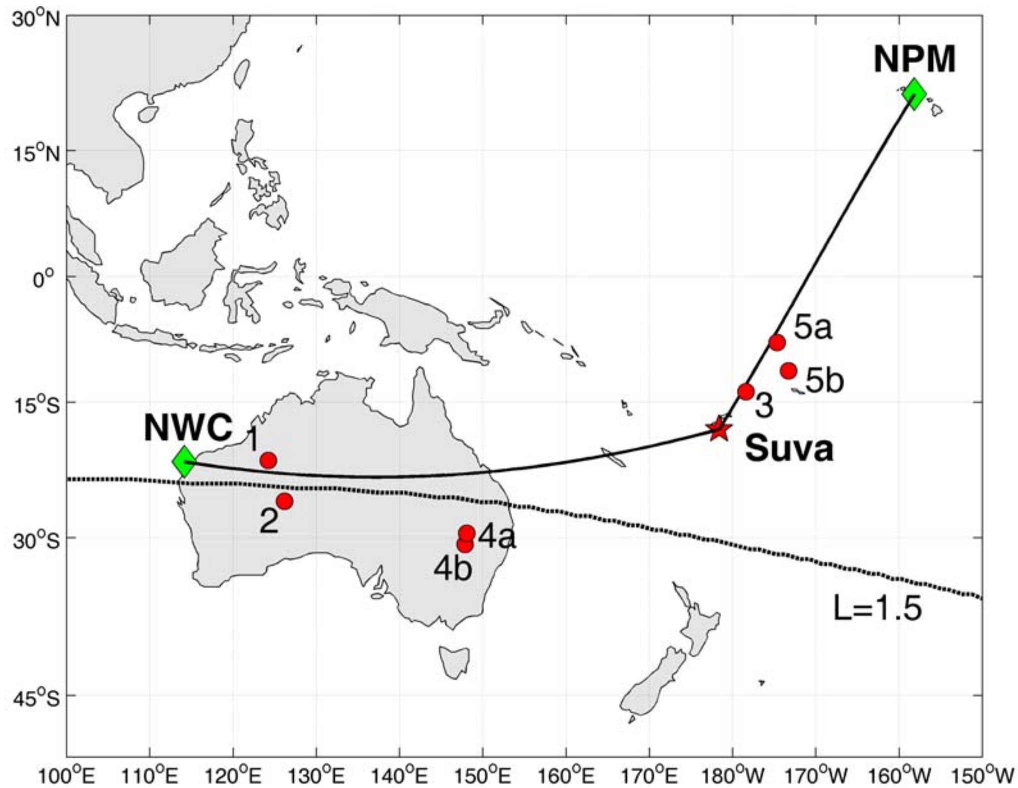
Figure 6. A typical example of daytime early/fast VLF event observed simultaneously on NWC (solid trace) and NPM (dotted trace) signals on 21 Nov. 2006 at 06:30:55.8 hrs UT.

Figure 7. A record of amplitude showing three early/fast VLF events observed simultaneously on NWC (solid trace) and NPM (dotted trace) signals in the daytime on 5 Nov.2006 at 19:53:09 hrs UT.

Figure 8. A typical example of step-like early event observed on NWC (solid trace) signal in the daytime on 2 November 2006 at 04:42:13.8 hrs UT. Dashed vertical lines with arrows indicate the time of associated WWLLN detected lightnings.

Figure 9. Sample of one hour record at Suva showing typical examples of step-like early VLF events (A and B) observed simultaneously on NWC and NPM signals in the daytime on 23 November 2006 at 22:12:25.5 and 22:15:43.1hrs UT. Dashed vertical lines with arrows in panels a and b indicate the time of associated WWLLN detected lightnings for the event B. Panel c shows the amplitude of NWC and NPM signals recorded at Dunedin, New Zealand using OmniPAL data logger, which indicates that at the time of occurrence of events amplitudes of NWC and NPM signals were constant at Dunedin.

Figure 10. Diurnal variation of number of early VLF events detected during 1-30 November 2006 **a)** on NWC signal, **b)** on NPM signal.



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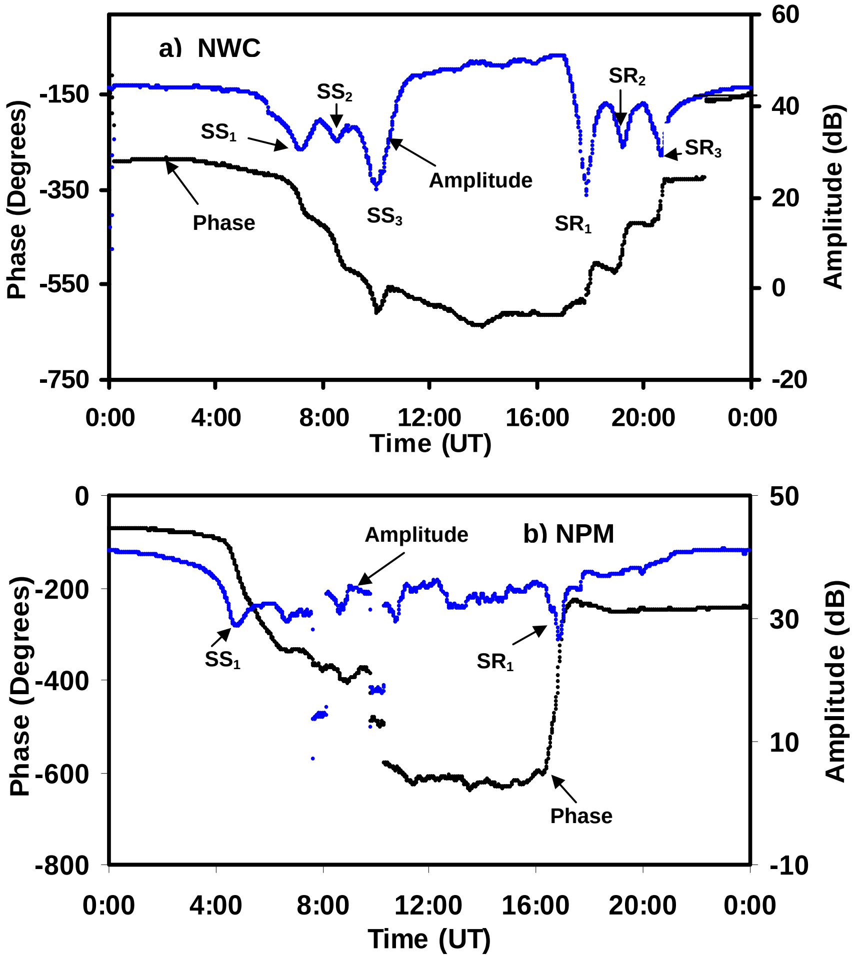
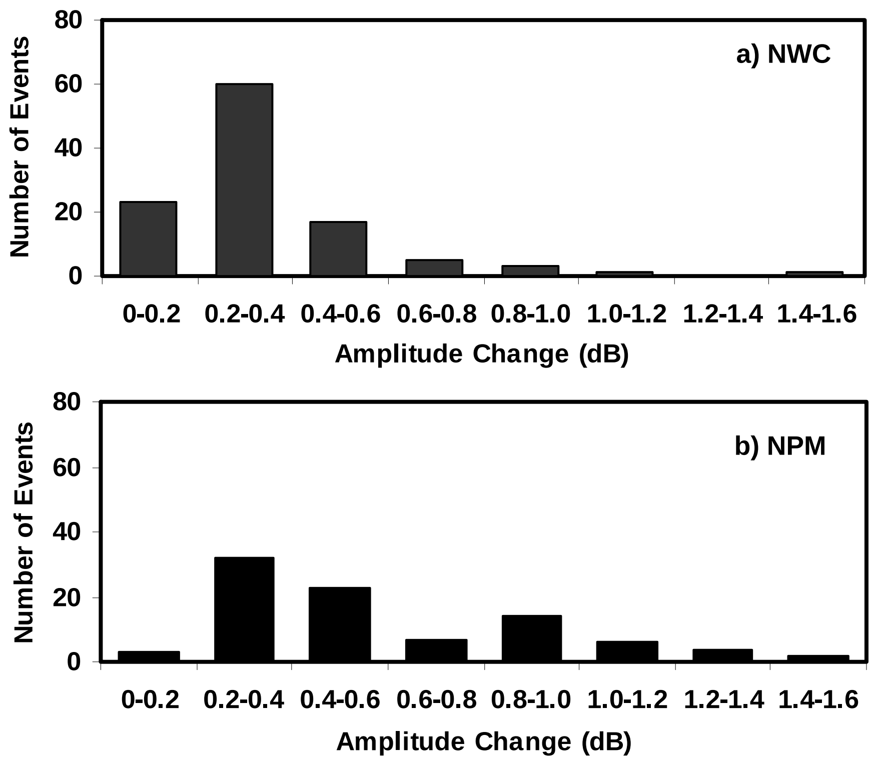


Figure 2. Typical variation of amplitude and phase of NWC and NPM signals on 21 November 2006.



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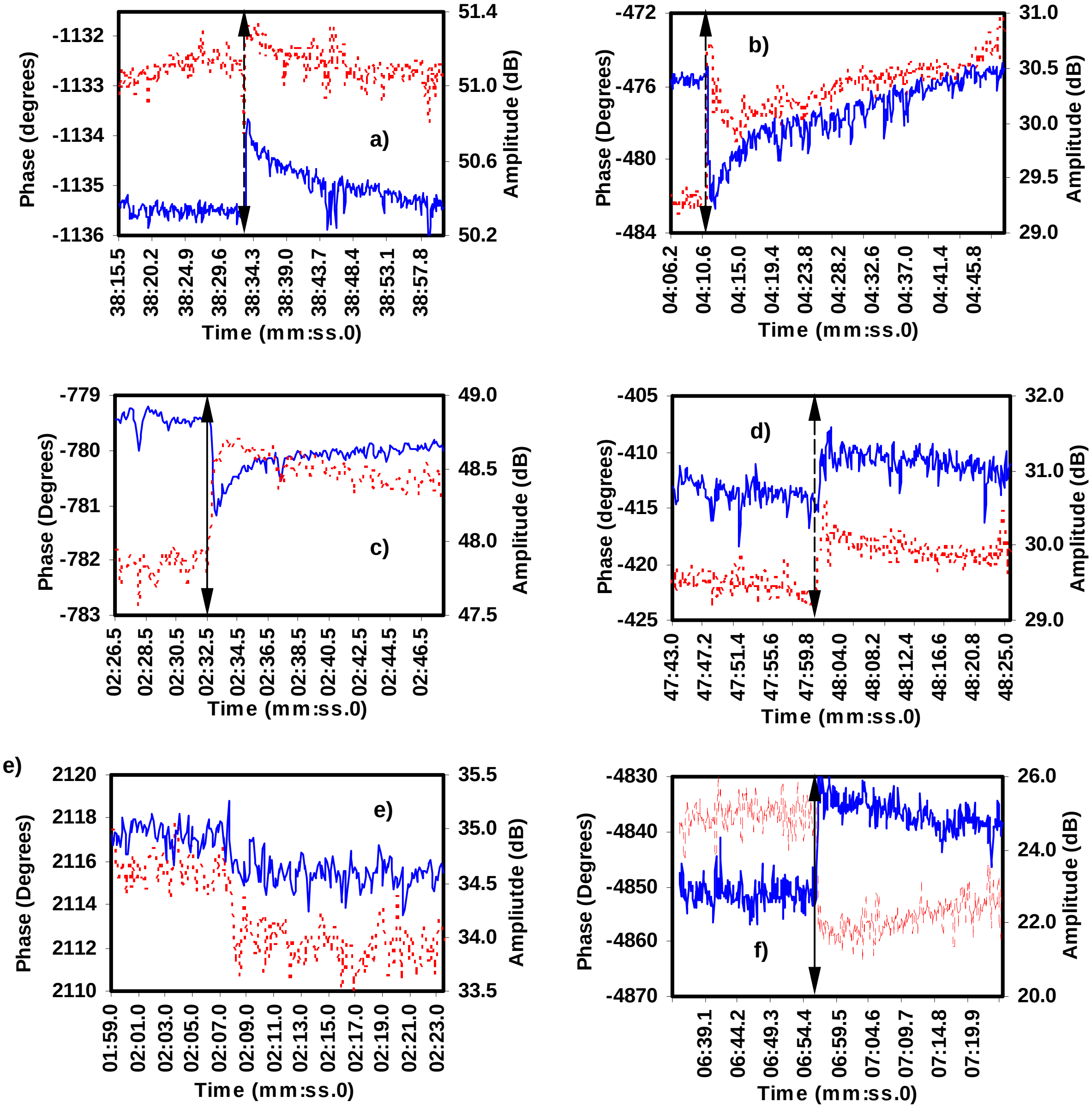

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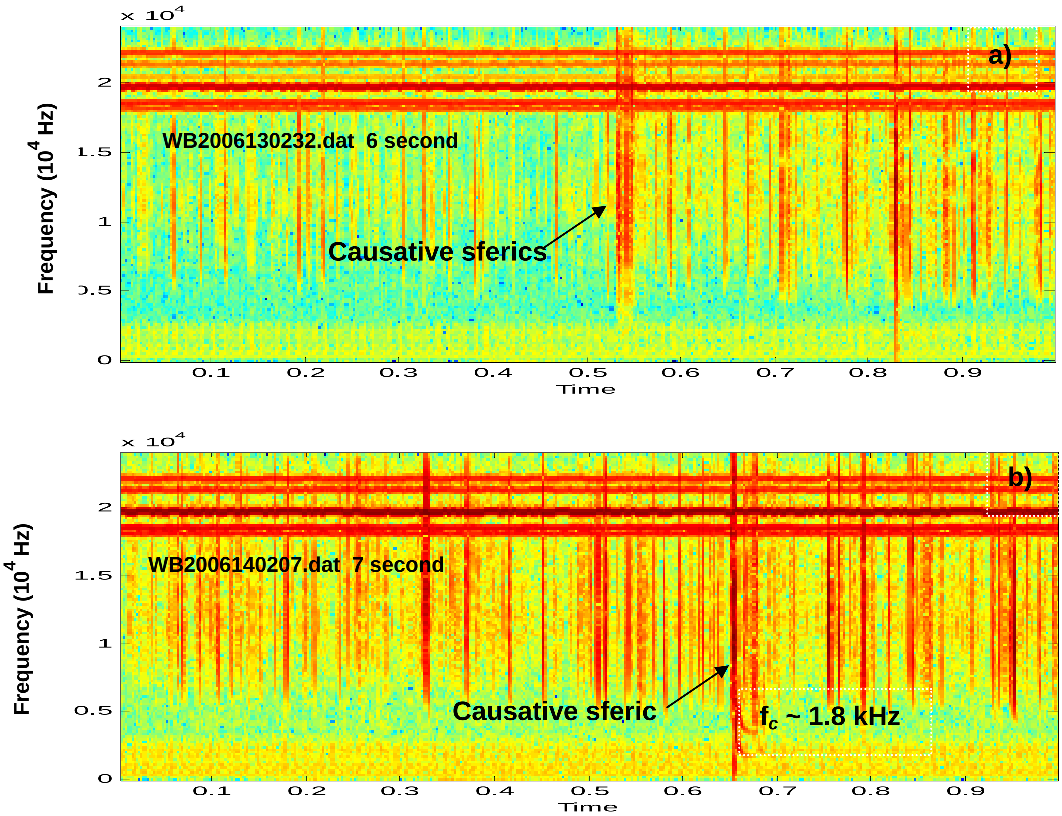

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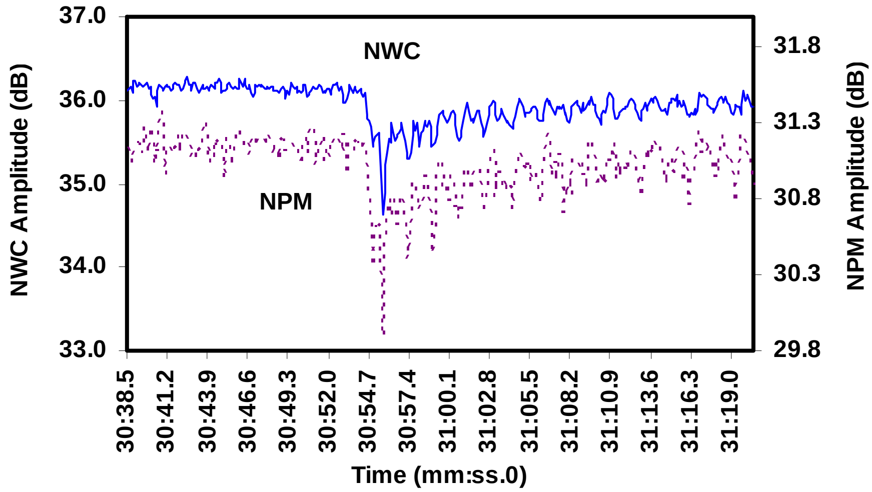

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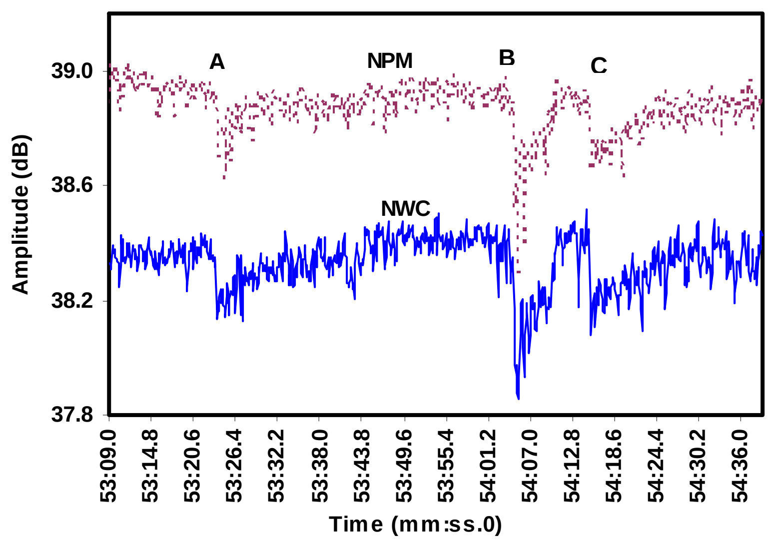

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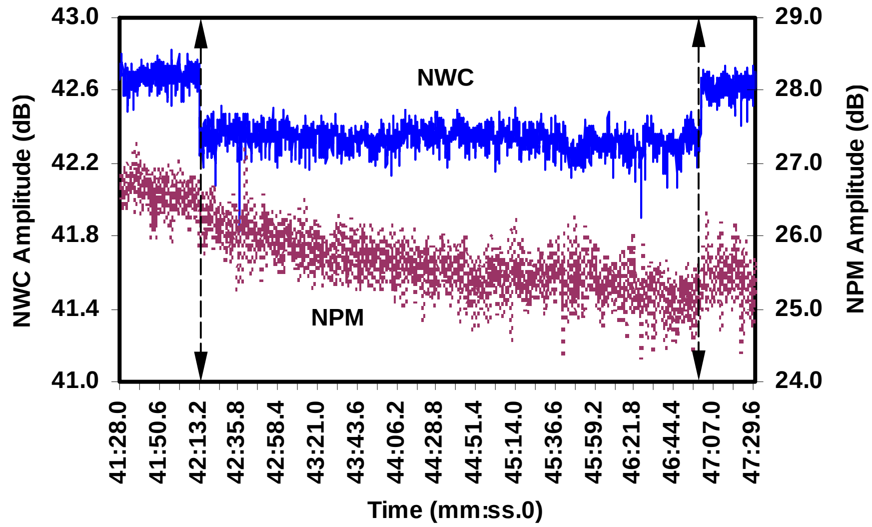

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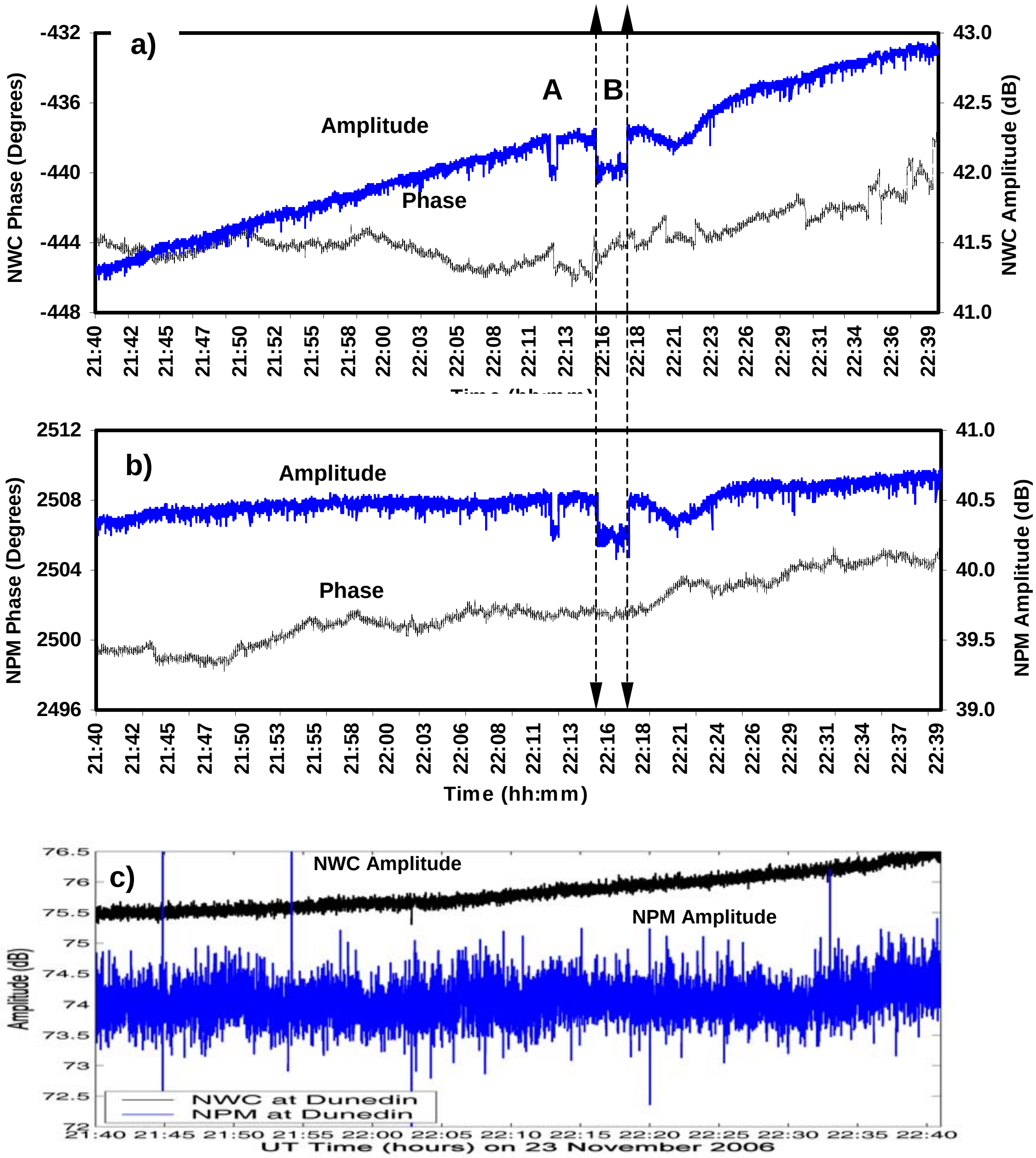

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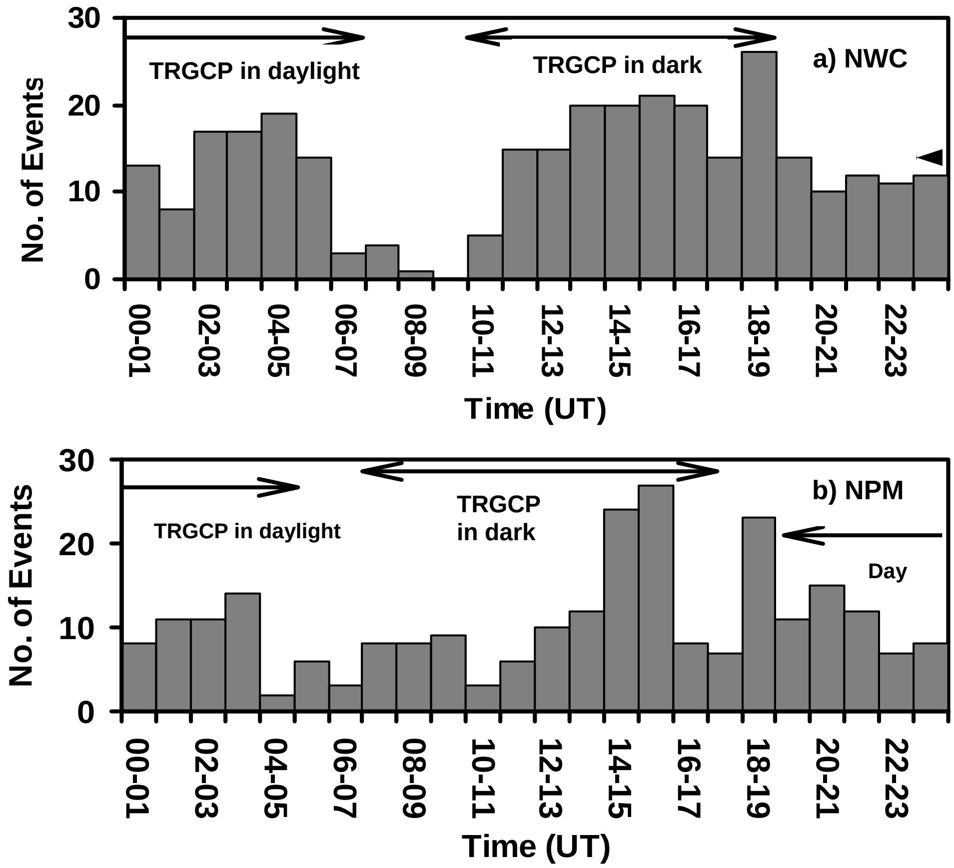

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