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VLF observation of long ionospheric recovery events

Benjamin R. T. Cotts[1] and Umran S. Inan[1]

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[1] We introduce a new class of Early/fast VLF events with recoveries of up to 20 min, much longer than typical Early/fast and Lightning-induced Electron Precipitation (LEP) events which recover to pre-event levels in $\lesssim$200 s. Three distinct types of long recovery events are observed, each exhibiting different characteristics, with the observed features of at least some of the event types consistent with the possibility of persistent ionization at altitudes below 60 km as put forth by Lehtinen and Inan (2007).

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1. Introduction

[2] Early/fast events are ionospheric disturbances observed on subionospherically propagating VLF transmitter signals and are evidence of direct coupling between lightning and the ionosphere. They have long been observed [*Inan et al.*, 1988] to occur within 20 ms of a causative lightning discharge, endure <20 ms [*Inan et al.*, 1993; *Dowden et al.*, 1994], and recover in $\sim$60–180 s [*Sampath et al.*, 2000]. A new category of Early/slow events have also been observed [*Haldoupis et al.*, 2006], sometimes exhibiting an onset duration of >1 s recovering similar to their "fast" counterparts. In this context, we refer to such events as 'Early' VLF events. Published data contains examples of recoveries >200 s [e.g., *Inan et al.*, 1988, Figure 17; *Inan et al.*, 1996, Figure 6 (Event M); *Dowden et al.*, 1997, Figure 2e], none of which were highlighted or noted as unusual. The 20 Nov., 1992 events discussed below were shown by *Inan et al.* [1993, Figure 9], but without mention of the unusually long recovery. We specifically highlight herein this new subclass of Early VLF events with up to $\sim$20 min recoveries, determined within an error bound of $\lesssim$10%, due to the presence of ionospheric fluctuations occurring on time scales of a few minutes.

2. Observations

[3] The data presented includes two case studies of amplitude/phase records: the NAU transmitter (Aquadilla, PR, 28.5 kHz) recorded on 20 Nov., 1992 in Gander, Newfoundland and the NAU transmitter (40.75 kHz) recorded on 23 Feb., 2006 in Boston, MA. Figures 1c (top two panels), 2 (top two panels), 3c (top two panels), and 4 (top two panels) show the full extent of an event, and the event onset with associated sferic from causative lightning discharge in Figures 1c (bottom two panels), 2 (bottom three panels), 3c (bottom two panels), and 4 (bottom two panels).

2.1. NAU at Gander (GA), Newfoundland

[4] Between 02:00 UT and 09:00 UT, >100 lightning-associated perturbations of the NAU-GA signal (18.38°N, 67.18°W to 48.95°N, 54.55°W) were observed, the majority of which were typical LEP [*Johnson et al.*, 1999] ($\sim$30%), or Early VLF events ($\sim$70%). However, Events A, B, and C in Figure 1a exhibited recovery times of up to $\sim$20 min, but were not evident on any other VLF path.

2.1.1. Event A

[5] The amplitude of Event A (not shown expanded) begins to recover before interruption ($\sim$02:47 UT) by a separate lightning-associated perturbation, after which the signal level remains nearly constant for $\sim$10 min. However, an extrapolated best-fit line indicates that the amplitude would have recovered after $\sim$17 min, whereas the phase appears to have fully recovered after only $\sim$200 s. Expanded time records of Event A indicate typical Early and fast features, with an "Early" onset within <10 ms of the causative lightning discharge, and a "fast" onset duration, also <10 ms.

2.1.2. Event B

[6] The amplitude of Event B (Figure 1c) exhibits a long ($\sim$20 min), essentially uninterrupted recovery, while the phase recovers in a much shorter time ($\sim$100 s). Several smaller events (indicated by arrows) are superimposed on the Event B recovery, all of which recover in $\sim$60–180 s; i.e., the long recovery is not a superposition of recovery from successive events. Figure 1c shows that the amplitude response is clearly coincident with the causative lightning (Figure 1c, bottom panel). The phase onset is not shown because the change is not discernible on an expanded scale, due to low signal-to-noise ratio and loss-of-phase-lock due to sferic intrusion. The phase change is nevertheless visible on compressed/time-averaged records (Figure 1c, second panel).

2.1.3. Event C

[7] Event C (Figure 2) exhibits a large amplitude and phase change, both of which are followed by a long ($\sim$14 min) mostly uninterrupted recovery, unlike the shorter phase recoveries of Events A and B. The onsets of both amplitude and phase are clearly coincident with the causative lightning (Figure 2, bottom panel).

2.2. NAU at Boston (BO), MA

[8] An overview of events observed on the NAU-BO signal (18.38°N, 67.18°W to 42.36°N, 71.05°W) is shown in Figure 3a. The NAU transmitter signal at Taylor, IN (40.45°N, 85.5°W; Figure 3a, bottom panel) exhibits no perturbations, confirming that Events D, E, and F, are not transmitter-related. Events D, E, and F are all closely spaced

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[1] Department of Electrical Engineering, Stanford University, Stanford, California, USA.

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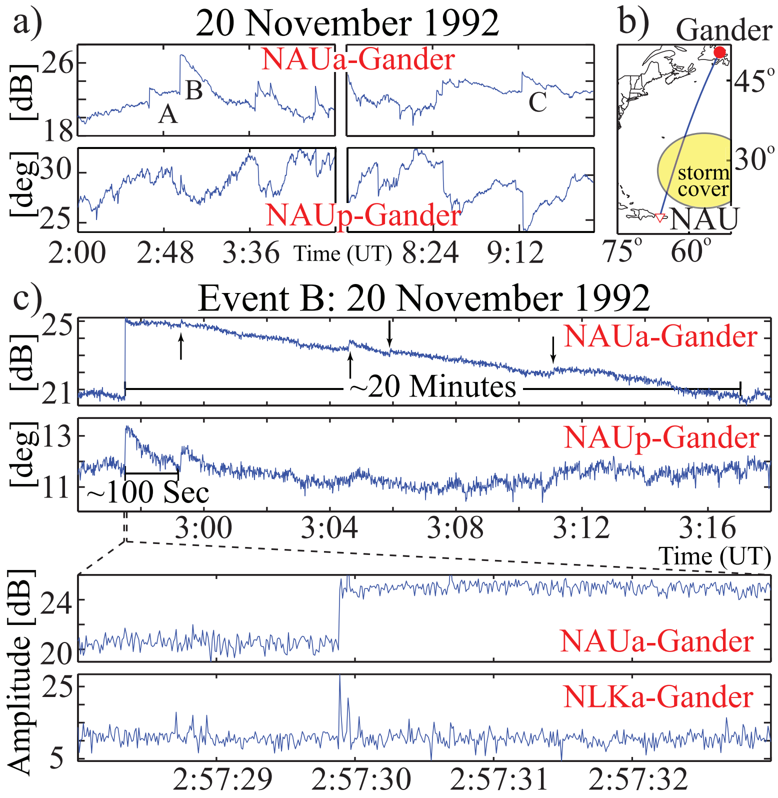

Figure 1. (a) Overview of Events A, B, and C. (b) Map showing NAU-GA GCP, and approximate storm location taken from NOAA-GOES cloud cover. (c) (top two panels) Full extent of Event B and (bottom two panels) onset of Event B (10 ms resolution).

in time and likely in location (based on recorded lightning discharges, Figure 3b). No cloud-to-ground lightning discharges were recorded by the National Lightning Detection Network (NLDN) at the exact time of any of these events; likely due to lower detection efficiency of NLDN at long range [*Cramer and Cummins*, 1999; *Boeck et al.*, 2000] since the causative lightnings are clearly evident as sferics in VLF data (Figures 3c, bottom panel, and 4, bottom panel), and there was a storm overlying the path based on

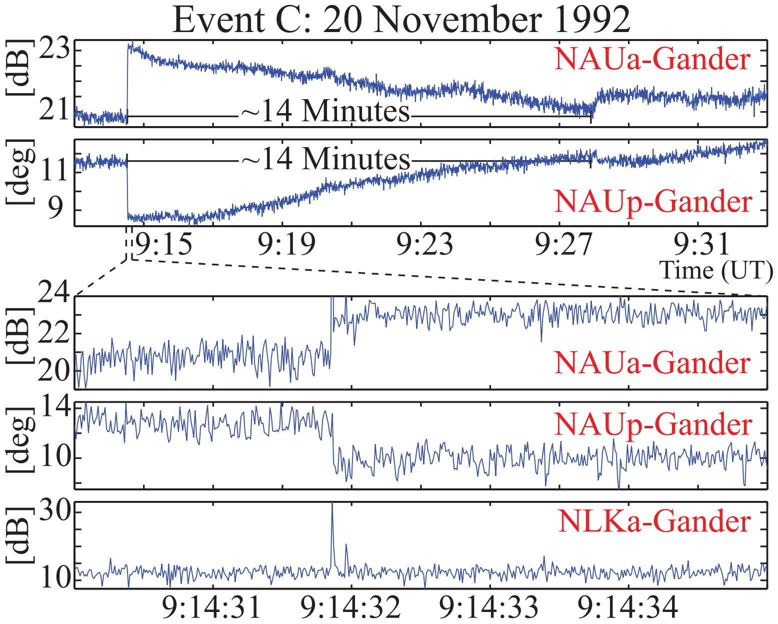

Figure 2. (top two panels) Full extent of Event C and (bottom three panels) onset of Event C (10 ms resolution).

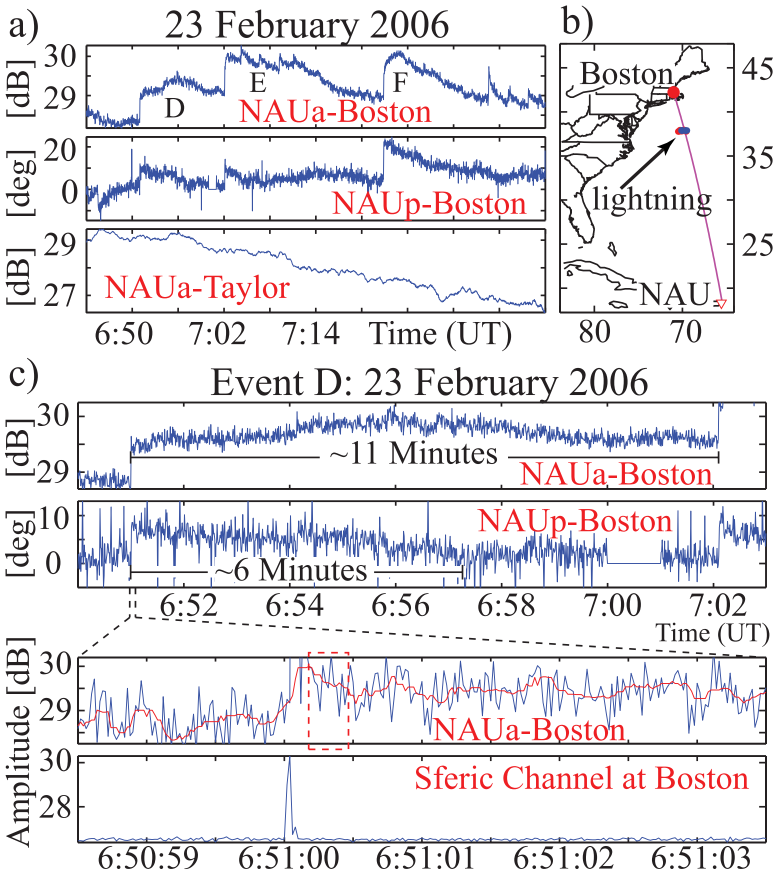

Figure 3. (a) Overview of Events D, E, and F. (b) Map of NAU-BO GCP and NLDN-detected lightning from 06:45–07:45 UT. (c) (top two panels) Full extent of Event D and (bottom two panels) onset of Event D (20 ms resolution). Note the rapid initial partial amplitude recovery highlighted by a dashed-box.

NLDN identification of lightning between 06:45–07:45 UT (Figure 3b).

2.2.1. Event D

[9] Event D signal amplitude in Figure 3 remains at the newly attained level for ~11 min, until interruption by Event E (Figure 3a). However, the signal phase recovers to pre-event level in ~6 min. This step-change behavior is similar to previous observations [e.g., *Inan et al.*, 1988, Figure 17; *Inan et al.*, 1996, Figure 6 (Event M)], and was predicted to sometimes occur by *Glukhov et al.* [1992] and *Pasko and Inan* [1994]. Event D also exhibits a rapid (~0.5 s) initial partial amplitude recovery immediately after onset (Figure 3c, third panel), best illustrated by a 12-point median filter (superimposed and highlighted by a dashed-box). Event D onset is clearly coincident with causative lightning as evidenced by a large impulsive sferic (Figure 3c, bottom panel).

2.2.2. Event E

[10] Event E (Figure 4) exhibits a ~15 min amplitude and ~200 s phase recovery. A best-fit line was used to analytically extrapolate the recovery to pre-event levels amidst interruptions by LEP and typical Early VLF events (indicated by arrows). The shorter recovery of the Early VLF or LEP events occur independently (e.g., at a different altitude) of the long recovery, returning to the best-fit line before subsequent disturbances. A rapid initial partial amplitude recovery is evident in the expanded records highlighted by a dashed-box (before settling to the long recovery), with the event once again coincident with causative lightning. The phase onset, masked by sferic intrusion, is not shown.

2.2.3. Event F

[11] Event F (expanded record not shown) resembles Event C, with long amplitude and phase recoveries (~12 min). One difference, is a large "overshoot" in amplitude, where the rapid onset of Event F is followed by a slow increase for nearly two minutes, reaching ~0.5 dB above the initial event onset. This overshoot may simply be an unrelated ionospheric variation, but a continuing effect analogous to that predicted by *Haldoupis et al.* [2006] (with respect to Early/slow events) is also possible. No overshoot is evident in the phase response which recovers over ~12 min. Event F also exhibits a ~0.5 s rapid initial partial amplitude recovery, and is coincident with the causative lightning.

3. Discussion

[12] The events presented herein constitute a new class of lightning-related upper atmospheric disturbance, all exhibiting long recoveries but with three distinct types of characteristics: long-amplitude/short-phase recovery (Type 1), long-amplitude/long-phase recovery (Type 2), and step-change events (Type 3) in which the amplitude does not return to pre-event levels. In addition, each of these

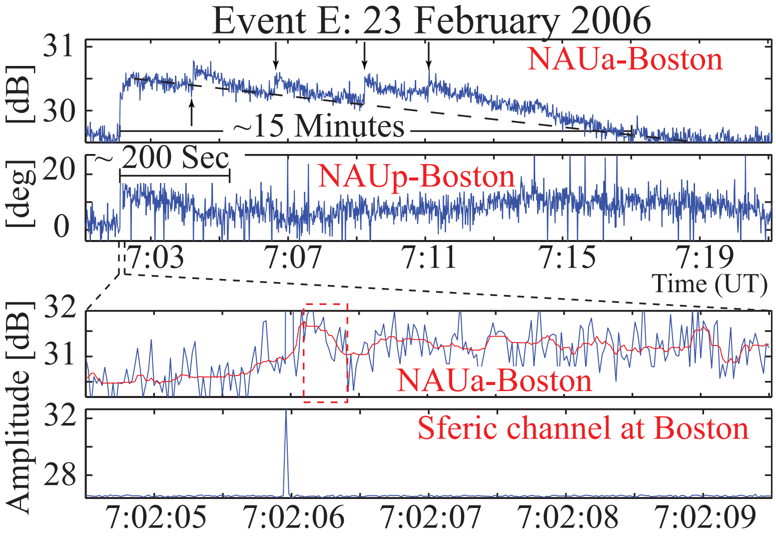

Figure 4. (top two panels) Full extent of Event E and (bottom two panels) onset of Event E (20 ms resolution). Note the rapid initial partial amplitude recovery highlighted by a dashed-box.

three basic types sometimes exhibit a rapid (~0.5 s) initial partial recovery. The three different types of events presented may involve ionospheric disturbances at different altitudes, for which the atmospheric relaxation response may be different.

[13] Differences between the three types of long recovery events can be considered in the context of a simple model. For long distance VLF paths (i.e., $\gtrsim 10\lambda$) the observed signal is considered to be a superposition of two vectors, a 'direct' signal arriving along the Great Circle Path (GCP) and a signal 'scattered' from the ionospheric disturbance [*Poulsen et al.*, 1993]. This model is complicated by the fact that both the direct and scattered signals are themselves a superposition of several waveguide modes (vectors) [*Rodriguez*, 1994], with the modes constituting the scattered signal being in general different from the modes constituting the direct signal. The recovery of the total signal amplitude/phase at the receiver depends on the temporal evolution of the scattered signal vector, which is determined by the relative contributions of different constituting modes, each of which may have a different relative phase and amplitude. The total field amplitude change observed is determined by the altitude-dependent conductivity along the entire VLF path [*Ratcliffe*, 1959] for each mode, and can be dominated by ions at altitudes where electron density is low. Conversely, the signal phase is largely determined by the difference in path length between the direct and scattered signals and is thus mostly a function of the VLF reflection height [e.g., *Pasko and Inan*, 1994]. In typical LEP or Early VLF events, the amplitude and phase signals recover in roughly the same time because the disturbed atmospheric region is typically confined immediately below the VLF reflection height [e.g., *Lev-Tov et al.*, 1995; *Moore et al.*, 2003].

[14] Although quantitative modeling of physical processes that lead to the long recoveries is beyond the scope of this paper, we can make some qualitative observations. The recovery of the atmosphere from newly introduced ionization is controlled by interplay between, on one hand, relatively fast ($\lesssim$1 s) electron attachment and detachment processes, and on the other hand, relatively slow ($\gtrsim$100 s) electron-ion and ion-ion recombination processes [*Pasko and Inan*, 1994; *Lehtinen and Inan*, 2007]. Based on past analysis at *D*-region altitudes where the conductivity is normally dominated by electrons (i.e., $\gtrsim$65 km at night), subionospheric VLF amplitude and phase perturbations are known to typically recover in $\lesssim$200 s. Since disturbances above the reflection height cannot be sensed by subionospherically propagating VLF signals, these longer recoveries may be due to processes at lower altitudes. It is known, for example, that at stratospheric altitudes (<60 km), atmospheric conductivity is typically dominated by ions [e.g., *McGorman and Rust*, 1998, section 1.4] and it is possible these long recoveries are due to processes at lower altitudes where ion chemistry typically becomes dominant. *Lehtinen and Inan* [2007] investigated this possibility numerically in connection with gigantic blue jets and found that transient ionization in the altitude range of 20–70 km recovered back to ambient conditions over slow ($\sim 10^3 - 10^4$ s) time scales. The presence of long-enduring ionization at lower altitudes make this process a possible explanation for the Type 1 recoveries discussed above in cases where the ionization enhancement is not large enough to significantly alter the reflection height of VLF waves, so that the phase of such a disturbance would recover in timescales typical of *D*-region altitudes (i.e. $\lesssim$200 s). However, the signal amplitude would recover slowly as it is affected by the slowly recovering ionization at lower altitudes, due largely to the time scale of mutual ion neutralization [*Lehtinen and Inan*, 2007; *Inan et al.*, 2007].

[15] Type 2 event signatures suggest a different physical mechanism than that for Type 1 events. These types of events may be due to the reflection height being drastically modified, e.g., lowered to $\lesssim$70 km due to much higher ionization caused by changes in ion compositions resulting from effects of electromagnetic or quasi-static fields produced by the causative lightning, possibly in association with gigantic blue jets [*Lehtinen and Inan*, 2007]. It is also possible that these types of events may be due to relatively

Table 1. Recovery Time Statistics for Selected Sea-Based and Land-Based Paths

GCP	Total Events	≥180 s, %	≥9 min, %
NAU-GA (sea)	188	20.2	7.5
NAA-AR (sea)	117	15.4	5.1
NAA-VQ (sea)	136	12.5	5.9
NAA-HU (land)	271	5.5	1.5

small ionization enhancements on an already electron-depleted ionosphere. Model calculations (based on those of *Glukhov et al.* [1992]) indicate a recovery time of ~12 minutes at 85 km for a relatively small (i.e., ~10 times ambient) electron density enhancement in a highly tenuous ambient ionosphere [e.g., *Pasko and Inan*, 1994, Profile 1].

[16] Type 3 events are illustrated by Event D (Figure 3) where the amplitude response does not recover to pre-event levels, possibly because the atmosphere has attained a quasi-equilibrium state, the recovery from which takes a much longer time [*Glukhov et al.*, 1992; *Pasko and Inan*, 1994].

[17] The ~0.5 s rapid initial partial recovery does not appear to be specifically related to any one type of event discussed above and is likely a separate process common to each. Such rapid time scales are possibly due to rapid electron attachment and detachment processes [*Pasko and Inan*, 1994; *Lehtinen and Inan*, 2007].

4. Sea-Based Versus Land-Based Paths

[18] To explore the possible connection with gigantic blue jets, which have been exclusively observed over oceanic storms we undertake a preliminary statistical analysis of recovery times on selected GCPs to assess whether long recovery events are observed only on all-sea-based paths. Because only low resolution data was used for statistical analysis, some reported long recovery events may possibly be due to LEP. The paths analyzed are: NAA (Cutler, ME) to Vieques (VQ), PR, NAA to Arecibo (AR), PR, and NAA to Huntsville (HU), AL. The paths were chosen for approximate matching of GCP length, and *L*-shell coverage. The NAA-VQ (44.39°N, 67.12°W to 18.12°N, 65.5°W) and NAA-AR (44.39°N, 67.12°W to 18.35°N, 66.75°W) paths are all-sea-based, (~2895 km), while the NAA-HU (44.39°N, 67.12°W to 34.73°N, 86.58°W) path is mostly land based (~1977 km). Table 1 shows the total number of observed events, and the percentage of events recovering in >180 s, and >9 min (where a 10 min recovery is counted in both columns), for each path. Table 1 suggests that while long recovery events are not confined to oceanic storms, they are more likely to occur in such regions.

5. Summary

[19] We have demonstrated the existence of a new subclass of Early VLF events with exceptionally long recoveries, and shown that these events exhibit a variety of amplitude and phase responses. While so far such events have only been studied extensively over oceanic paths, some long recovery events have also been observed on land-based paths, and further research is required in order to determine their causative mechanisms. These very long recoveries of lightning-induced disturbances in the upper atmosphere and the implied possibility of persistent ionization at altitudes <60 km may open the door to a new exploration of chemical interactions in the atmosphere including both exceptionally long (≥20 min) and exceptionally short (<0.5 s - initial partial recovery) chemical relaxations. In view of the fact some of the observed signatures are consistent with the predictions of *Lehtinen and Inan* [2007], some of these long recovery events may well be VLF signatures of gigantic blue jets.

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B. R. T. Cotts and U. S. Inan, Department of Electrical Engineering, Stanford University, 350 Serra Mall #037, Stanford, CA 94305, USA. (bcotts@stanford.edu)