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Reply

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Abstract. The comment by R. L. Dowden does not properly represent the results presented in our recent paper [*Inan et al.*, 1995] and attempts to prematurely classify the VLF events reported in our papers as being produced by elves. There is no experimental evidence that the VLF events reported in our papers are necessarily associated with the optical phenomena of elves. In our recent paper [*Inan et al.*, 1996a] we provide a physically based mechanism which accounts for the forward scatter property of the VLF events observed in our data.

Optical Phenomena and VLF Perturbations

Transient mesospheric glows with ~10 ms duration called sprites [e.g., *Sentman et al.*, 1995], and lasting ~300 μs and called elves [e.g., *Fukunishi et al.*, 1996] were originally detected as optical phenomena using video/photometric measurements. There is no experimental evidence that the spatial extent of illuminated regions is the same as the spatial extent of the modified conductivity in the lower ionosphere. This realization implies that sprites with columnar narrow horizontal extent (~1-10 km) may well be associated with lower ionospheric modifications (conductivity changes) with much greater lateral extents ~100-150 km. VLF observations shown in our paper [*Inan et al.*, 1995] indicate the size of the regions of electrical conductivity change to be ~100-150 km, generally greater than the size of the sprites shown in associated video images by University of Alaska and by ASTeR, Inc. groups.

We have recognized earlier [*Inan et al.*, 1996b] that lateral extents of ionization regions associated with sprites are too small to be consistent with the observed forward scattering property. Columns of ionization with lateral extents less than the VLF wavelength can lead to an omnidirectional scattering pattern which can be detected by a receiver placed nearby sprites, well off the propagation path, and even in a back scattering direction. Much larger ionization regions indeed are expected to be produced as a result of heating by lightning-EMP associated with elves [*Inan et al.*, 1996c]; however, these ionization regions mostly lie at altitudes above the VLF reflection height, and their production requires much larger peak lightning currents than those of many of the associated cloud-to-ground lightning discharges [*Inan et al.*, 1996b]. The temporal structure and forward-scattering character of the short-duration (or RORD-type [*Dowden et al.*, 1994]) events are fully consistent with heating due to quasi-static fields, which occurs over a large region and which can endure for up to a second or two [*Inan et al.*, 1996b]. It is important to note also that at least some of the forward scatter type events reported in papers [*Inan et al.*, 1993; 1996b] occurred in relatively small winter thunderstorms in association with positive as well as with negative cloud-to-ground discharges which were not intense enough to produce sprites/elves. Some of these events were observed in association with relatively weak lightning discharges (estimated peak currents of ~6 kA) which would not be expected to lead to intense enough heating to produce elves [*Inan et al.*, 1996c].

The optical structure of sprites provides some indication of the distribution of ionization in the lower ionosphere since the appearance of a new population of free electrons due to ionization leads to a proportional increase in the optical output (assuming that the electron distribution is heated to the same energy level) [*Pasko et al.*, 1996]. One should, however, be careful with such estimations since the threshold energy of optical excitation of the 1st positive band of N_2 (observed in sprites) is ~7 eV and is at least two times less than the threshold energy of breakdown ionization [e.g., *Inan et al.*, 1995].

Differences in Data Sets and Methodology

Important differences between the nature of the data sets used by the Stanford University and University of Otago groups have to be recognized in comparing the scientific conclusions. Since the mid-1980's [*Inan et al.*, 1988], Stanford observations have been carried out with 20-ms time resolution, and often with separate and definitive data (from the National Lightning Detection Network or NLDN) on the intensity and location of associated lightning discharges. Noting the complexity of VLF signal responses, especially due to the intrusion of intense energy from sferics when thunderstorm activity is nearby, a conservative approach has been adopted, by identifying early/fast VLF perturbations as an 'event' only when its onset coincided (i.e., within 20-ms) with a clearly associated sferic, and often also with NLDN recorded lightning flashes. As a result, *all* of the events reported in our papers and included in our statistics are necessarily associated with a distinctly identifiable sferic. For typical early/fast events, exhibiting 10-100 s recoveries, this identification scheme is unambiguous and works well. For short-duration events, one needs to be more conservative in order to make sure that the amplitude or phase change is not effected by the intrusion of the sferic energy into the narrowband channel being measured. For this purpose, *Inan et al.* [1996b] used the criteria that the perturbation event on the signal in question had to endure distinctly longer than the sferic as measured in another narrowband channel. This conservative approach leaves out possible short-duration (or RORD type) VLF perturbations associated with sferic bursts with durations up to a second or so; however, it is really the only way to be sure that what is being measured is an ionospheric change rather than the component of the intense sferic energy intruding into the narrowband channel.

As far as we can gather from their published work [*Dowden et al.*, 1994], the University of Otago group conducts the bulk of their observations with 400-ms resolution and identifies 'events' on the basis of the event signature itself rather than on the basis of simultaneity with lightning or sferics. In fact, up to 60% of their RORD events do *not* have accompanying sferics.

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Early/fast VLF Events as Evidence of Sustained Ionospheric Heating

Inan et al. [1996a] provides a discussion of the different possible causes which would produce large scattering objects, including elves, and concludes that the most likely explanation is based on the concept of sustained heating of the lower ionospheric electrons by thundercloud electric fields. Sudden ($<$ 20 ms) subionospheric VLF signal changes, occurring simultaneously (within $<$20 ms) with lightning discharges, are proposed to represent relatively small changes in the heating level of the lower ionosphere. In this context, quasi-electrostatic fields supported by thundercloud charges maintain the ionospheric electrons at a persistently heated quiescent level well above their ambient thermal energy. Changes in the thundercloud charge distribution (e.g., in lightning discharges) lead to heating/cooling above/below this quiescent level, and are registered as VLF perturbation events. The heating is maintained by the relatively small lower ionospheric electric fields which exist during the thundercloud charge accumulation phase, in a manner physically similar to fair weather electric fields. When lightning discharges occur, large quasi-electrostatic fields exist for short ($<$1 s) periods of time, and the heating 'level' of the electrons changes. The difference in the heating levels before and after the discharge transients accounts for the observed early/fast amplitude changes. The observed 10-100 s recoveries of early/fast events are understood as the dissipation of charge or re-charging of the thundercloud. The resultant perturbation of the VLF signal is suggested to be due to extended heated regions with $\sim$100-150 lateral extents [*Inan et al.,* 1996a,b], in good agreement with expected diffraction pattern as described in [*Inan et al.,* 1995; 1996b].

Summary

1) The comment by R. L. Dowden does not properly represents the results presented in [*Inan et al.,* 1995], which include clear experimental evidence of early/fast VLF events produced by weak lightning discharges not likely to produce elves.

2) There is clear experimental evidence in our data that both regular early/fast events (recovering in 10-100 s) and short-duration (RORD type [*Dowden et al.,* 1994]) events involve forward scattering regions of relatively large lateral extent [*Inan et al.,* 1996b]. This finding is at odds with R. L. Dowdens results on RORDs; the differences may be due to differences in data sets and methodology.

3) A natural resolution of the many issues involves the interpretation of early/fast VLF events in terms of sustained heating of the lower ionospheric electrons by thundercloud fields [*Inan et al.,* 1996a]. This new mechanism is consistent with the forward scattering nature of the early/fast and short-duration events and attributes the 10-100 s recoveries to the recharging of the thundercloud.

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