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High-latitude geomagnetically induced current events observed on very low frequency radio wave receiver systems

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[1] Noise burst events observed at Sodankylä, Finland, in the frequency range 20–25 kHz during January–April 2005 last up to 4 s, occur more often at midnight, are associated with high geomagnetic activity, and exhibit a quasi-constant amplitude perturbation ~15 dB above the background noise levels. We considered the possibility that the events could be caused by lightning noise breakthrough. The association of the noise burst events with local midnight and high geomagnetic activity argues against a lightning link, as well as the lack of close thunderstorm location relative to Sodankylä during noise periods. While energetic electron precipitation is also associated with high geomagnetic activity, we showed that they occur at different times and exhibit significantly different amplitude characteristics. Finally, we compared in detail the geomagnetic induced current (GIC) in the Scottish power system in southern Scotland, during a storm event that occurred on 15 May 2005, with the noise burst event rate at Sodankylä. We found that the onset time and variability of the Scottish GIC activity was well matched by the variability in the noise burst event rate, particularly the high-frequency component of the GIC fluctuations. The technique used in our study of observing at a narrow band of frequencies allows GIC measurements to be made in built-up areas where mains interference is a problem for other experiments, such as magnetometers.

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1. Introduction

[2] Very low frequency (VLF) observing systems have been used at high latitudes for many years [*Barr et al.*, 2000] particularly to monitor waves that have propagated to the ground from space, such as whistlers, chorus waves, triggered emissions [*Helliwell*, 1965], waves from lightning discharges [e.g., *Dowden et al.*, 2008], and also to monitor energetic particle precipitation through effects on radio wave subionospheric propagation [e.g., *Clilverd et al.*, 2009]. In this study we analyze radio signals recorded at 20–25 kHz in the high-latitude northern hemisphere using an experiment intended to monitor man-made radio wave transmissions. We show that on occasions when strong man-made radio transmissions are not present, large noise spikes can be observed, which are associated with high geomagnetic activity. We discuss the mechanism that produces these features, particularly in terms of either lightning generated noise, energetic electron precipitation, or local electromagnetically induced currents.

[3] Short-duration waves like chorus and triggered emissions can be strong, but are typically restricted to frequencies < 15 kHz [*Helliwell*, 1965] and are thus not considered as a significant noise source in the 20–25 kHz

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range investigated here. Auroral hiss bursts can produce strong emissions in the 20–25 kHz frequency range, but these have not been observed to be intense enough, nor of short enough duration, to be categorized as large noise spikes as we define them later in this study (T. Turunen, personal communication, 2010). However, lightning generated noise bursts known as "atmospherics" or "sferics" [*Rakov and Uman*, 2006] are a significant noise source in the 20–25 kHz range. While lightning tends to occur more often at low latitudes than at high latitudes [*Christian et al.*, 2003], the signals can propagate long distances in the subionospheric waveguide and so we consider their effect further in this paper as a potential mechanism to explain large noise spikes observed in our narrowband receivers.

[4] The precipitation of energetic electrons into the D region can occur in bursts and be observed from balloon-borne experiments, as well as through their effect on subionospheric propagation. Relativistic Electron Precipitation (REP) into the atmosphere has been observed to take several forms. Relativistic microbursts observed from the SAMPEX satellite last less than 1 s, occur at about L = 4–6, are observed predominantly in the morning sector, and have been associated with VLF chorus waves [*Nakamura et al.*, 2000; *Lorentzen et al.*, 2001]. Precipitation events lasting minutes to hours have been observed from the MAXIS balloon. They occur at about L = 4–7, are observed in the late afternoon/dusk sector, and may be produced by EMIC waves [*Millan et al.*, 2002; *Rodger et al.*, 2008]. Both of these types of precipitation can occur at the same time during geomagnetic storms, as observed by *Clilverd et al.* [2006] and *Rodger et al.* [2007] during the large electron flux decrease event of 21 January 2005.

[5] During geomagnetic storms the modification of ionospheric currents can produce telluric currents that are correlated with sudden changes in magnetometer recordings. Geomagnetic storms cause large currents to flow in the ionosphere, which in turn induce geomagnetically induced currents (GICs) in electric power systems [*Thomson et al.*, 2005]. The GICs result in severe half-cycle saturation and increased demands on transformers through increased leakage fluxes. GICs have caused unusual noises and heating in transformers, real and reactive power swings, voltage fluctuations, the operation or nonoperation of protective relays, and other similar effects [*Pulkkinen et al.*, 2005; *Pirjola*, 2007]. The effects can be long lasting (hours) but changeable over only a few seconds depending on the variability of the ionospheric currents. GIC effects on VLF systems have been observed in the form of increases in the intensity of power line harmonics in the frequency range 180–720 Hz [*Hayashi et al.*, 1978]. The cause was attributed to induced currents over loading a power supply near to the VLF observation site, during a sudden storm commencement. Hayashi et al. suggested that suitably distributed VLF receivers would be expected to be useful for monitoring GIC in power systems.

[6] In this study we report for the first time unusual noise events observed on narrowband VLF recordings in the frequency range 20–25 kHz. We analyze data from Sodankylä, Finland, from 1 January to 30 April 2005 in order to compare the noise events with other features in the radio wave data, such as lightning noise, and perturbations due to the precipitation of energetic electrons. We also compare the response of the VLF receivers to geomagnetically induced currents observed in a power system in Scotland during a large geomagnetic storm. Wideband spectrograms (1–30 kHz) would have helped distinguish between these mechanisms, particularly as they show broadband noise well, and electron precipitation effects poorly. However, wideband recordings were not available during the period studied here. Even so, we show that geomagnetically induced currents are the most likely explanation for the observed noise events, and that they could be induced in the VLF receiver itself or in nearby power systems; making the instrument a simple, real-time, cheap, and portable monitor of these potentially disruptive ionospheric currents.

2. Experimental Setup

[7] We use high time resolution, narrowband subionospheric VLF data spanning 20–25 kHz received at two sites: Sodankylä, Finland (67°N, 23°E, L = 5.2); and Ny Ålesund, Svalbard (79°N, 11°E, L = 18.3). These sites are part of the Antarctic-Arctic Radiation-belt Dynamic Deposition VLF Atmospheric Research Konsortia: AARDDVARK [*Clilverd et al.*, 2009]. The data shown in this study are taken from 1 January to 30 April 2005, which includes several periods of high geomagnetic activity and good quality data from both sites. Figure 1 shows the location of the receiver sites (diamonds), and the transmitter-receiver paths that are under study (transmitter locations are given by the circles).

[8] The receiver at Sodankylä (SGO) records data at 0.1 s resolution, while the receiver at Ny Ålesund records at 1.25 s resolution. Most of the data used in this study is from SGO because of the high time resolution required to study burst events. The aerials used in both cases are magnetic loops and thus directional. We study data from the transmitter frequencies logged when the signals from the transmitters are either off or nulled by the directionality of the aerial to very low amplitudes.

[9] Supporting data from Kilpisjärvi, Finland (69.02°N, 20.86°E, L = 6.1), are taken from the central beam (beam 25) of the Imaging Riometer for Ionospheric Studies (IRIS) [*Browne et al.*, 1995], which operates at 38.2 MHz. The riometer measures the relative opacity of the atmosphere, and generates a data set of the variation of the absorption of 38.2 MHz radio waves, which can be

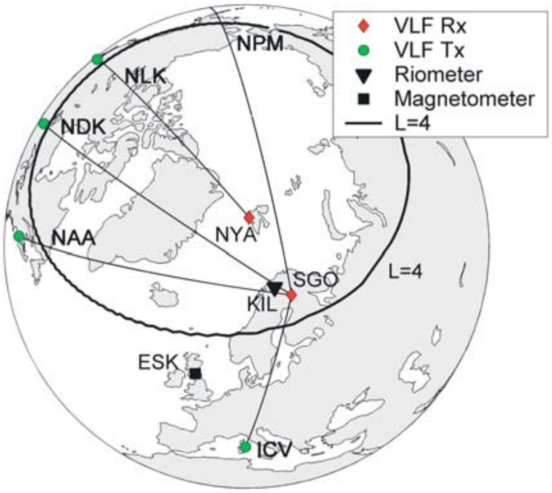

Figure 1. The location of subionospheric propagation paths to the AARDDVARK receiver sites at Sodankylä and Ny Ålesund. The $L = 4$ contour is shown to indicate the high-latitude region of substorm activity and potential energetic particle precipitation.

interpreted as a measure of the additional ionization produced by precipitating energetic particles, such as 30–200 keV electrons.

3. Results

[10] The experimental setup at SGO means that the great circle path of the transmitter in Hawaii (NPM, 21.4 kHz) passes through the high-latitude region of the northern hemisphere (Figure 1). However, the magnetic loop aerial orientation used at SGO has been optimized to monitor the nearer transmitters in Europe, such that the Hawaii signal is very weak. Figure 2 shows the amplitude of NPM during 21 January 2005. The amplitude of NPM is typically close to the natural noise levels defined by lightning atmospherics, i.e., about 30–35 dB in Figure 2, and shows some slowly varying behavior associated with the diurnal variation in lightning activity. During this day recovery is occurring from the solar proton event that began at 0700 UT on 20 January 2005 but this does not influence the data shown in Figure 2. At 1710 UT a coronal mass ejection hit the Earth [*Clilverd et al.*, 2006] and at this time large noise burst events (NBEs) can be observed on the NPM signal. The noise bursts are typically > 15 dB higher than the background levels, i.e., with quasi-constant peak amplitudes ~50 dB, and continue until the end of the day. During this period, Kp > 8. Some other periods of burst events are also observed before 1710 UT, especially at the beginning of the day just after 0000 UT, although they are relatively few in number.

[11] Figure 3 is a close-up of one of the NBEs that occurred just after 1715 UT. Figure 3 shows the amplitude and phase changes during the burst event. Vertical dotted lines indicate the start and end of the event, which has a total duration of 4.5 s. Some structure can be seen in the event, although it is primarily one of a sudden increase in amplitude, followed by a gradual recovery. These characteristics are typical of the noise burst events seen in the Sodankylä data, e.g., sudden large positive increases in amplitude with an accompanying advance in phase.

[12] Due to the quasi-constant peak amplitude of NBEs we are able to use a simple threshold detection algorithm to determine the number of NBEs for each hour during the period 1 January to 31 April 2005. The threshold was set at 50 dB. Figure 4 shows the time variation of the number of NBEs per hour averaged over 3 h during the period of study, and shows a comparison with the 3-hourly geomagnetic a_p index. Vertical dashed lines are plotted on Figure 4 to indicate the start of periods of high geomagnetic activity. A data gap occurred from 5 to 11 January 2005 in the VLF recordings, which explains why a period of high geomagnetic activity on 7 January 2005 does not appear to correlate with high NBE occurrence. For the rest of the study period there is a high correlation between the occurrence of NBEs and increased geomagnetic activity.

[13] The diurnal variation of the occurrence of NBEs per hour from 1 January to 31 April 2005 is shown in Figure 5. The occurrence of NBEs varies reasonably smoothly throughout the day. The occurrence rate is near

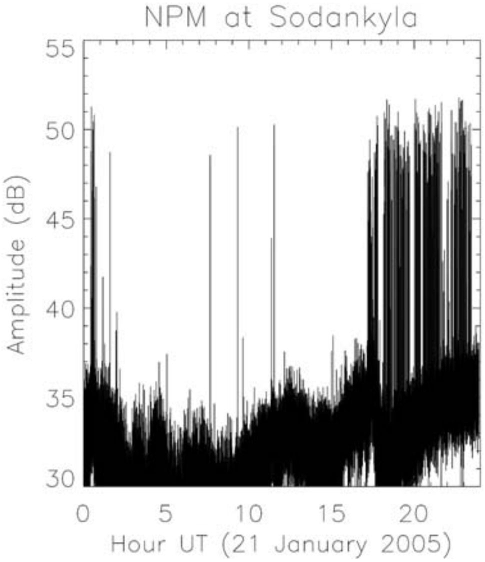

Figure 2. The amplitude of the Hawaii (NPM) transmitter signal received at Sodankylä, Finland, on 21 January 2005.

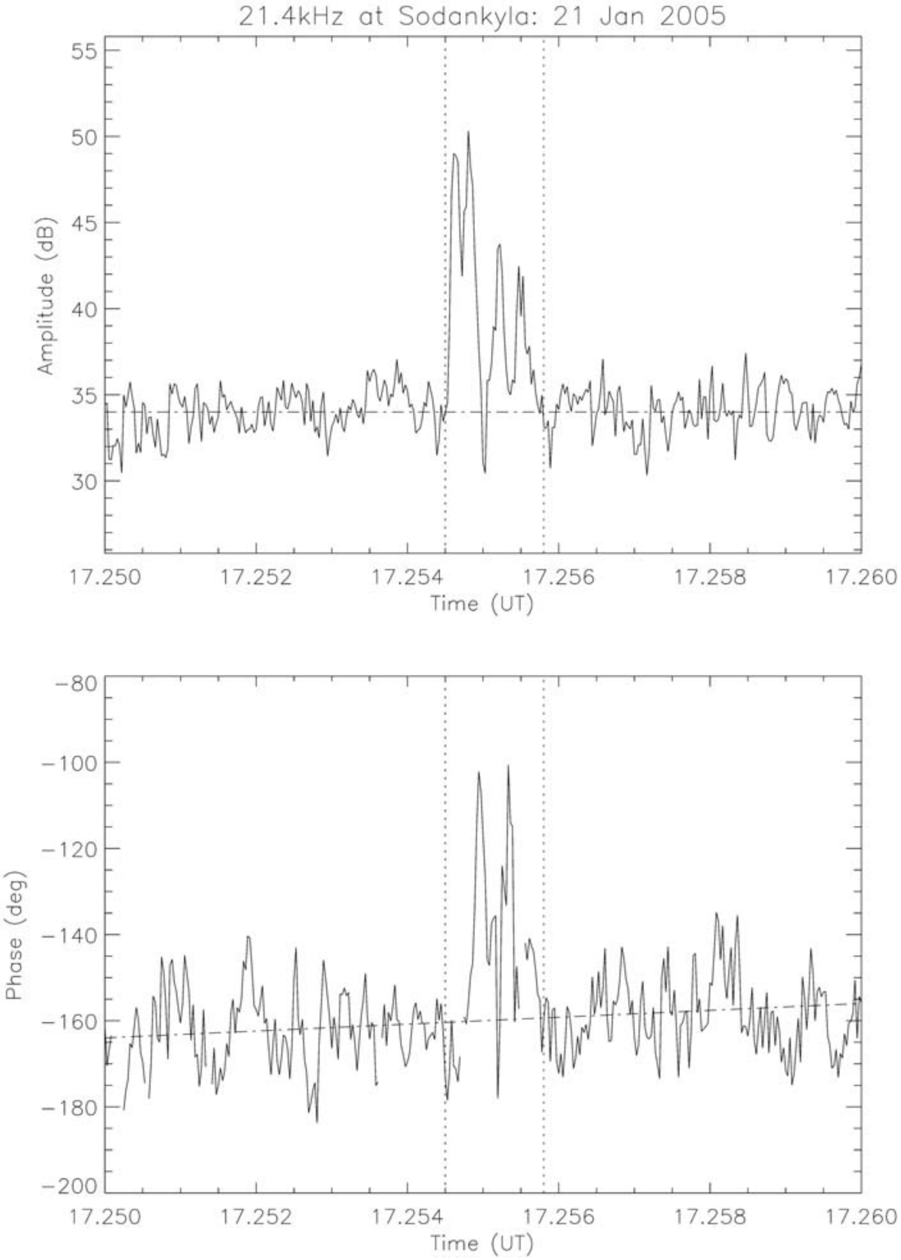

Figure 3. High time resolution plot of the amplitude and phase of a noise burst event. The length of time between the vertical dashed lines is 4.5 s.

zero during the daytime (1000–1600 UT, 1200–1800 LT), and peaks at 2200 UT (0000 LT). Magnetic midnight at Sodankylä is at 2100 UT. Figure 5 shows that NBEs are most often observed close to magnetic midnight. We discuss the possible significance of the diurnal variation of NBEs in section 3.3.

3.1. Comparison With Lightning Noise Bursts

[14] As the power spectral density of lightning peaks in the VLF spectral band [*Pierce*, 1977], it may be possible for lightning to interfere with Sodankylä's VLF data by "breaking through" into the narrowband observations. When comparing data from the World Wide Lightning

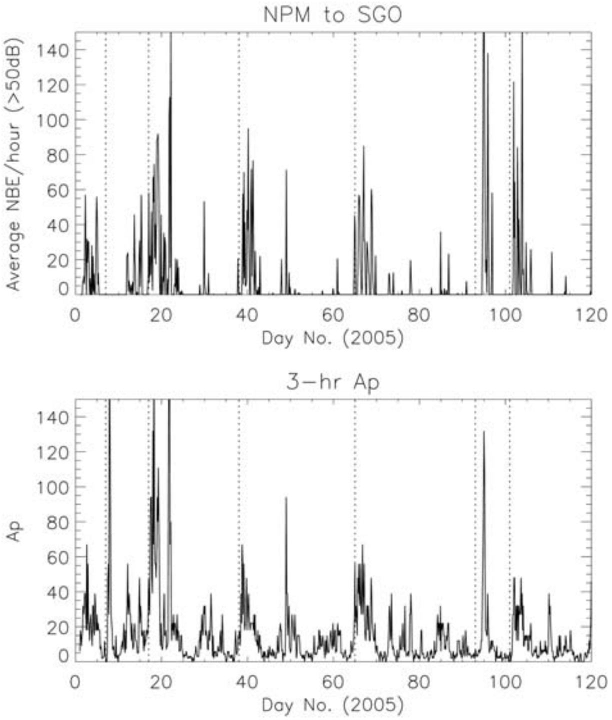

Figure 4. (top) The occurrence frequency of noise bursts on NPM received at Sodankylä during 2005. (bottom) The variation of 3 h Ap. Vertical dashed lines indicate times of increased geomagnetic activity.

Location Network (WWLLN [*Dowden et al.*, 2008; *Rodger et al.*, 2009]) for January–July 2005 inclusive, to search for periods of lightning activity near Sodankylä, it was found that only two lightning storms coincided with periods of VLF signal perturbation, and both were later in the year than April 2005. WWLLN locations used in the present study were produced by the original lighting location algorithm [*Rodger et al.*, 2006]. The WWLLN has low lightning stroke detection efficiency, detecting only a few percent of global lightning activity [*Rodger et al.*, 2009]; however, an investigation by *Jacobson et al.* [2006] has shown that the WWLLN supplies spatially accurate and representative detection of lightning storms as a whole, meaning that the accuracy is sufficient for this comparison.

[15] Lightning breakthrough perturbations, when present, were seen on all VLF channels received at SGO, in the form of 0.5–1.0 s increases in amplitude. Many perturbations were coincident in time across multiple channels. For the five VLF transmitter signals recorded at below 30 kHz at Sodankylä, the absolute amplitude of the peak perturbations were approximately the same for each event, but also varied from event to event, which is consistent with the perturbations being caused by lightning pulses of differing strengths (i.e., discharges with differing currents and orientations). These characteristics differ from the NBEs that we are studying here, in that the NBEs associated with high geomagnetic activity typically last longer by a factor of 3–4 when compared with the lightning effects, and unlike the lightning effects the geomagnetic NBEs are observed to have a near-constant amplitude from event to event. Only WWLLN-detected lightning strokes within 500 km of SGO were observed to produce interference on strong VLF signals, although that distance depends on the amplitude of the transmitter signals at the time. Weaker transmitter signals can be influenced by a relatively weak lightning signal, whereas stronger transmitter signals would remain unaffected.

[16] Figure 6 shows a lightning breakthrough perturbation on 1428 UT, 24 May 2005, which was coincident with a strong lightning strike within 100 km of Sodankylä, observed on many of the transmitter signals at the same time. All of the transmitter signals shown respond to the lightning noise with an increase in amplitude, and reach

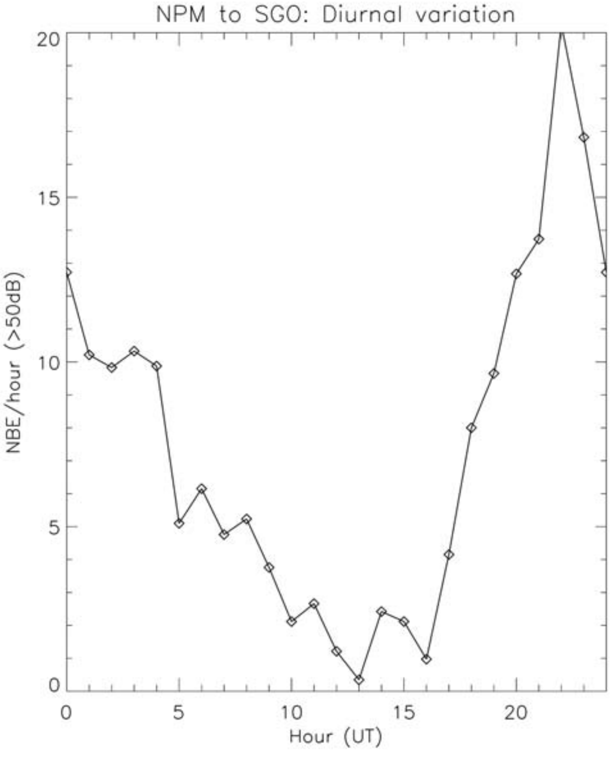

Figure 5. The diurnal variation of the occurrence frequency of noise bursts at Sodankylä during the first 4 months of 2005.

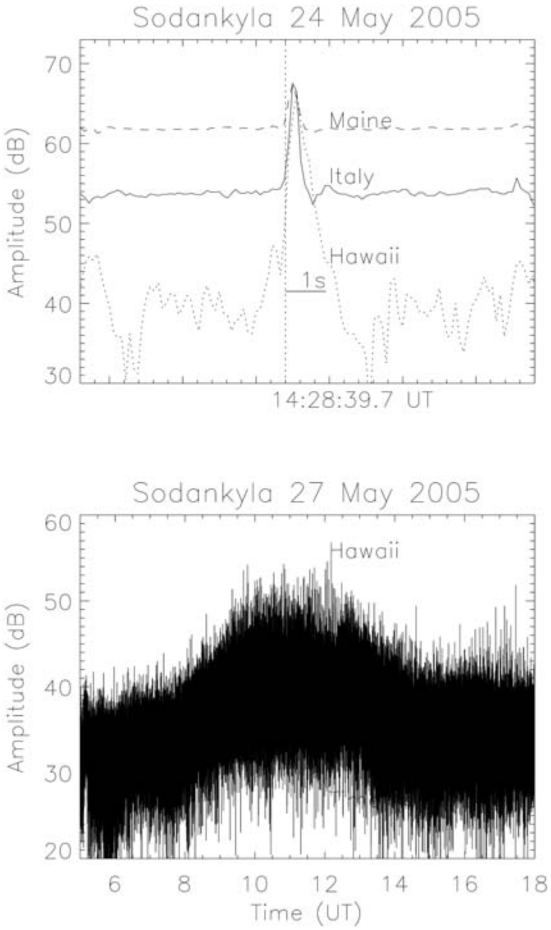

Figure 6. The effect of lightning NBEs on the AARDDVARK data during May 2005. (top) Close lightning breaks through even the strongest transmitter signals, producing effects lasting ~1 s. (bottom) Nearby thunderstorm activity produces NBEs for several hours, producing elevated noise levels from 0900 to 1400 UT on 27 May 2005.

the same amplitude level, which is independent of their initial amplitude. The timescale of the lightning breakthrough is ~1 s for the Hawaii signal. Figure 6 (bottom) shows an extended period of data when an approaching thunderstorm generated lightning perturbations with a similar amplitude compared with the observed geomagnetic NBEs, i.e., ~50 dB. The difference in the slow gradual rise of the noise level caused by the thunderstorm on 27 May 2005 should be contrasted with the onset of geomagnetic NBEs shown in Figure 2. The thunderstorm that generated the ~50 dB signals observed in Figure 6 was located in Russia, ~500 km southeast of the receiver at Sodankylä as determined using WWLLN data.

3.2. Comparison With Electron Precipitation Events

[17] *Rodger et al.* [2007] reported short-lived perturbations on transmitter signals received at Sodankylä during high geomagnetic activity, including the period in 21 January 2005 that we show in Figure 2. The perturbations were discussed in terms of the precipitation of relativistic electrons (~1 MeV) into the atmosphere and were termed “FAST events.” In this case the precipitation generated additional ionization at ~60–70 km altitudes which resulted in a sudden change in propagation conditions for the VLF transmitter signals, and a subsequent change in received phase and amplitude. The FAST events reported typically had a rapid onset, and lasted ~1 s. In this section we investigate if it is likely that the FAST events reported by *Rodger et al.* [2007] could be the cause of the NBEs reported here. The close association with periods of high geomagnetic activity certainly suggests that we should look more closely at the two.

[18] In Figure 7 we show the amplitude of the NPM Hawaii, NAA Maine, and NDK North Dakota transmitters at ~1900 UT, 21 January 2005. The data shown are from a period just after the onset of high geomagnetic

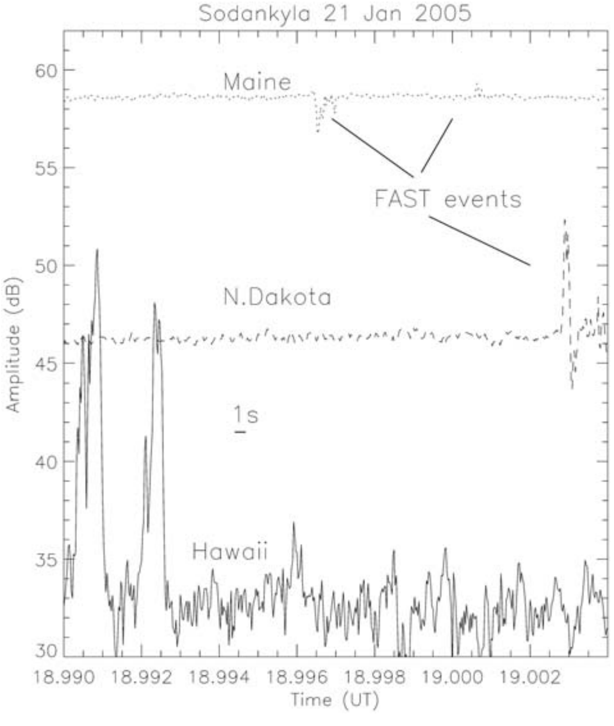

Figure 7. Showing the comparison between NBEs observed on NPM Hawaii, with FAST events observed on NAA Maine, and NDK North Dakota, on 21 January 2005.

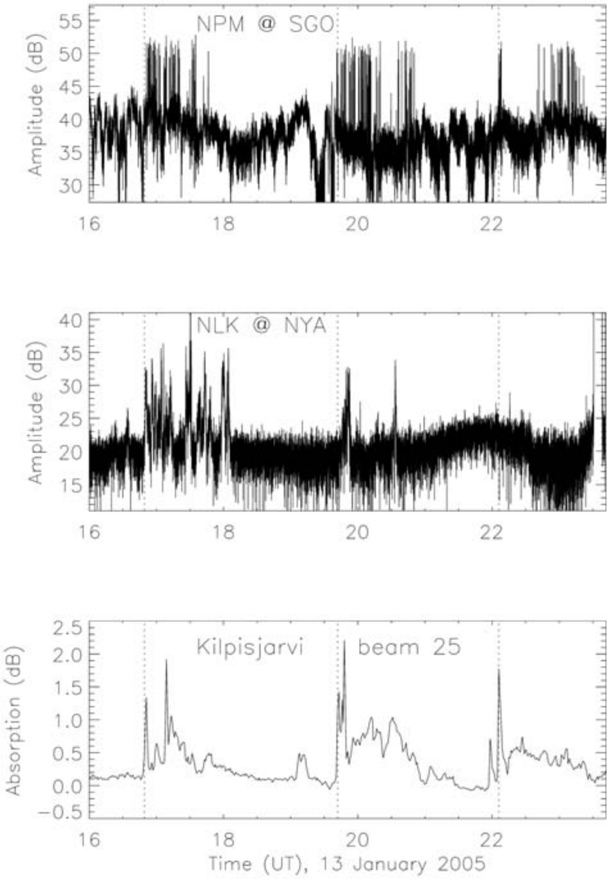

Figure 8. The timing of VLF noise bursts at Sodankylä and Ny Ålesund in comparison with substorm signatures observed on the Kilpisjärvi riometer, Finland, on 13 January 2005.

activity when FAST events were reported by *Rodger et al.* [2007]. The FAST events occurring on NAA and NDK are highlighted on Figure 7. The amplitude variation of the FAST events is both positive and negative, and sometime both. This is consistent with the idea that they are produced by small regions of ionization caused by energetic electron precipitation. The type of NBE studied here can be seen on NPM Hawaii at the start of the period shown. It is clear that when FAST events occur there is no coincident event on NPM Hawaii, suggesting that geomagnetic NBEs and FAST events are not linked even though they both occur during high geomagnetic activity.

[19] At high geomagnetic latitudes, geomagnetic substorms can be observed as increases in the absorption levels of riometers as a result of energetic electron precipitation in the 30–200 keV range [*Kavanagh et al.*, 2007]. As we have previously shown (Figure 5) that the NBE occurrence frequency peaks at midnight in the same way that substorm signatures do, we might anticipate an association between riometer observations and the NBEs. Figure 8 shows NBE data from 1600 to 2400 UT on 13 January 2005 recorded at Sodankylä and at Ny Ålesund, Svalbard. The AARDDVARK receiver at Ny Älesund was tuned to 24.8 kHz in order to monitor the NLK transmitter located in Seattle, USA; however, during this period the transmitter was off-air and the receiver was logging the noise levels until about 2330 UT when NLK began transmitting again. Figure 8 (bottom) shows the Kilpisjärvi ($L \sim 6.1$) riometer absorption data from the central beam (beam 25). Vertical dotted lines indicate the onset times of three substorm periods.

[20] Figure 8 shows that NBEs can be closely associated with substorm events. There appears to be some causal link between the short-lived periods of high absorption in the riometer data, particularly at the start of each substorm, and the occurrence of NBEs. At Sodankylä the NBEs tend to last for the whole period that the riometer absorption is elevated, while at Ny Ålesund only the first substorm shows a rate of NBE occurrence that is similar to that observed at Sodankylä. The NBE data from Ny Ålesund show that NBEs can be observed at receiver sites other than Sodankylä, although there are clearly temporal differences in the timing of NBEs between the two sites shown in Figure 8. The Ny Ålesund NBE observations also strongly suggest that these events are due to broadband noise emissions, and not caused by changes in subionospheric propagation, given the NLK transmitter was not broadcasting at this time and also because of the different frequency being monitored compared with Sodankylä (24.8 kHz compared with 21.4 kHz). *Lubchich et al.* [2006] discussed the generation of broadband emissions associated with 10–100 keV electron precipitation during substorms. Using broadband observations from Finland they showed that substorm-associated chorus in the frequency range 0.3–1 kHz was observed in the region of Sodankylä, Finland, close to the location where our NBE observations were made. However, these broadband emissions are not in the right frequency range to explain the observations of NBEs during substorms.

[21] Analysis of WWLLN lighting data during this period shows that the nearest thunderstorm activity was in the Mediterranean Sea, just off the coast of Libya. The distance from the thunderstorm location to Sodankylä is ~6000 km, and to Ny Ålesund is ~8000 km, strongly suggesting that these NBEs are not associated with lightning noise.

3.3. Comparison With Geomagnetically Induced Currents

[22] Geomagnetically induced currents occur during high geomagnetic activity and can be detected at high

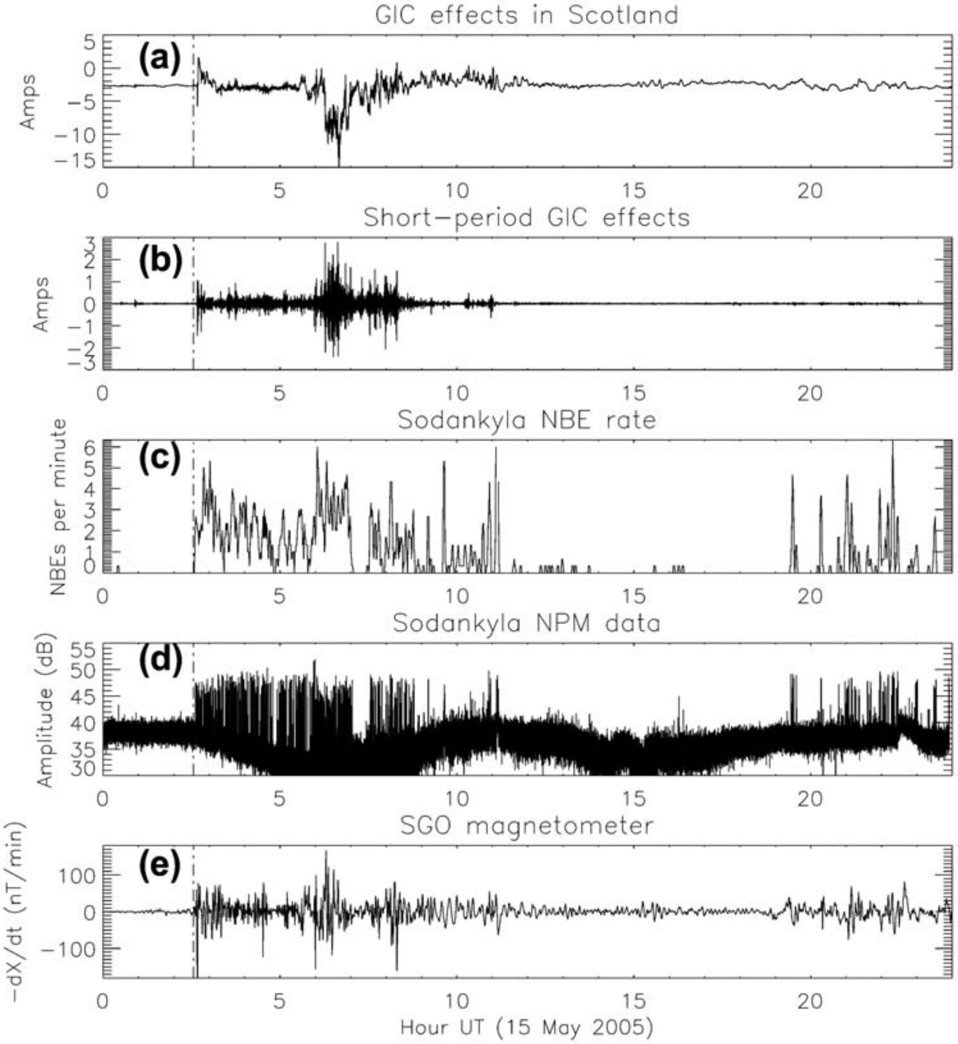

Figure 9. Showing the impact of geomagnetically induced currents in the Scottish power grid in Scotland on 15 May 2005. (a) The current variations and (b) the short-period fluctuations in the same data set. (c) The Sodankylä NBE occurrence rate and (d) the actual NBEs seen on NPM at Sodankylä. (e) The time derivative of the SGO magnetometer data (−dX/dt). The start time of a geomagnetic disturbance is indicated by the dot-dashed vertical line.

latitudes and midlatitudes. Currents flowing in the ionosphere map down to ground level and can induce effects in electrical systems. *Viljanen et al.* [2001] studied GICs in Scandinavia from 1999 to 2000. They showed that the diurnal variation of GICs in central and southern Finland peaked between 0000 and 0200 MLT (2100–2300 UT) with a relatively smooth decrease of occurrence toward the middle of the day. In the same study, Viljanen et al. also showed that the rate of change of the horizontal component of the geomagnetic field (a proxy for GICs) showed a similar diurnal variation for subauroral latitudes, but peaked at 0700 MLT (0400 UT) in the higher-latitude auroral zone in Finland. The diurnal variation of NBEs shown in Figure 5 is consistent with the time variation of GICs in the subauroral zone and strongly suggestive of GIC as a cause of the NBE phenomenon.

[23] In Figure 9 we compare the effect of geomagnetic activity on the induced currents measured in the Scottish Power system transformers in southern Scotland (Strathaven, $L \sim 2.8$) during 15 May 2005. The temporal resolution of the GIC observations was 1 s. Figure 9a shows the temporal variation of the system current, while

Figure 9b shows the induced current after being high-pass filtered (removing > 60 s fluctuations). Figures 9c and 9d show the NBEs seen at Sodankylä at the same time. The Sodankylä NBE rate (Figure 9c) was calculated by using a simple threshold test, triggering on the upward slope of the NBE, and discounting any further triggers until 4 s later in order to reduce the effects of temporal structure in the NBE signature. Rapid changes in the Scottish power current begins at the same time as the occurrence of Sodankylä NBEs, starting at 0230 UT as shown by the vertical dot-dashed lines, and shows very similar behavior over the next few hours. The peak of the Strathaven short-period currents occurs from 0600 to 0700 UT, which is also noticeable as a period of high Sodankylä NBE rate. There is also close coincidence during a period of reduced GIC activity starting at 0700 UT and lasting until 0730 UT. The NBEs are similarly reduced during the same period.

[24] An analysis of the data presented in Figure 9 indicates that there is little evidence of a one-to-one correspondence between the GICs and NBEs. The majority of the spectral power in GICs is in periods > ~10 s, so it is unlikely that there would be a clear one-to-one relation with NBEs.

[25] Although no observations of GIC activity were made in Finland for 15 May 2005 we are able to make an estimate using the magnetometer located in Sodankylä. Figure 9e shows the time derivative of the X component of the SGO magnetometer (−dX/dt), which is located at the same site as that where the NBE observations were made. The parameter −dX/dt corresponds to the eastward component of the geoelectric field and is representative of GIC activity levels. There is a close correspondence between the time derivative of the magnetometer data and the NBE occurrence rate, although the NBE rate does not provide any sign information and is in effect proportional to $(-dX/dt)^2$.

[26] Figure 9 also indicates that the number of NBEs increased again after 1900 UT along with probable GIC activity in Finland suggested by the SGO magnetometer data, while the GIC level in Scotland remained close to zero. The NBEs/GICs observed at the high-latitude Sodankylä site are likely to have been generated by substorm activity at this time of day, close to magnetic midnight. However, the Scottish power grid at midlatitudes was primarily responding to a large geomagnetic storm (Kp = 9) during the early part of 15 May 2005, and not the more poleward current systems of the substorms that followed.

4. Discussion and Summary

[27] In this study we have reported the characteristics of noise burst events (NBEs) observed at Sodankylä, Finland, during January–April 2005 in the frequency range 20–25 kHz. The NBEs tend to last up to 4 s, occur more often at midnight, are associated with high geomagnetic activity, and exhibit a quasi-constant amplitude perturbation. The NBEs have typical amplitudes that are > 15 dB above the background noise levels.

[28] We have considered the possibility that the NBEs could be caused by lightning noise breakthrough. The association of the NBEs with local midnight and high geomagnetic activity argues against a lightning link, although a similar sudden enhancement of "atmospherics" caused by changing radio wave propagation conditions as a result of solar flares (SEA [*Sao et al.*, 1970]) is well known. It is reasonable to consider that the occurrence of NBE periods might be the result of enhanced lightning "atmospheric" amplitudes caused by improved radio wave propagation conditions during geomagnetic substorms. However, using the WWLLN data we have been able to show that a thunderstorm generating lightning "atmospherics" that exhibited noise levels 15 dB above the normal background noise levels needed to be ~500 km from the receiver at Sodankylä. Analysis of NBE periods have shown that, particularly during the winter months, thunderstorm activity is typically more than an order of magnitude more than that distance from Sodankylä, well toward the equator and away from the high-latitude region of substorm-induced changes in radio wave propagation.

[29] We also considered the possibility that energetic electron precipitation could cause short-lived enhancements in ionization, which would perturb radio wave signal propagation. While energetic electron precipitation is also associated with high geomagnetic activity we have presented observations from Sodankylä that have both NBEs and FAST precipitation events [*Rodger et al.*, 2007] occurring, but they occur at different times, and exhibit significantly different amplitude characteristics. The observation of NBE at Sodankylä, Finland, and Ny Ålesund, Svalbard, at the same time during a series of substorms also argues against energetic electron precipitation as a result of radiation belt processes, as one of the transmitters was not broadcasting at the time and therefore no scattering of the transmitter signal could have occurred.

[30] Finally we considered the possibility that NBEs were caused by geomagnetically induced currents (GIC) driven by high geomagnetic activity and substorms. We compared in detail the GICs induced in the Scottish power system in southern Scotland, during a storm event the occurred on 15 May 2005, with the NBE rate at Sodankylä. We found that the onset time and variability of the Scottish GIC activity was well matched by the variability in the Sodankylä NBE rate. Induced voltages in the receiver aerials or nearby electrical systems could be expected to produce electrical noise that was quasi-constant in amplitude which is consistent with the

observed amplitude behavior of NBEs. A simple test of adjusting the Sodankylä aerial earthing configuration produced changes in the amplitude of NBEs during high geomagnetic activity, although they were always present during periods of high geomagnetic activity and could not be removed completely. Even though this is consistent with the idea that the NBEs are induced in the aerial system itself it does not exclude the possibility that GICs cause the saturation of high-voltage transformers in the vicinity of the VLF receivers, giving rise to strong impulsive noise which is affected by overvoltage protection in the aerial system. The observation of NBEs at Ny Ålesund, as well as Sodankylä, indicates that different types of VLF aerial system configurations are susceptible to geomagnetically induced NBEs, and reduces the chances that NBEs are due to lightning breakthrough or electron precipitation events. We conclude that GICs are the most likely source of NBEs.

[31] Our study leads to the conclusion that it is possible to use rate of occurrence of NBEs as an indicator of GIC events, particularly the high-frequency component of the fluctuations. VLF receiver systems are simple, low cost, portable, and easy to install, and as such can be used to provide measurements of GICs in remote areas, or on a campaign basis. The technique used here of observing at a narrow band of frequencies allows measurements to be made in built-up areas where mains interference is a problem for other experiments, such as magnetometers. Further work is planned to compare the coincident NBEs observed at Sodankylä and Ny Ålesund.

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