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Transmitter-induced modulation of subionospheric VLF signals: Ionospheric heating rather than electron precipitation

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[1] The controlled keying of ground-based VLF transmitters with periodic on/off sequences allows the detection of weak but measurable cross-modulation effects on other subionospheric VLF probe signals used for VLF remote sensing. In this paper, we reexamine previously published and additional cases of such events and determine that the initial interpretations of such cross modulation as being due to electron precipitation is likely incorrect. Rather, such events appear to be fully consistent with ionospheric heating caused by the keyed signal, even when the probe VLF signal path lies thousands of kilometers from the heating VLF transmitter. The 21.4 kHz transmitter NPM located in Lualualei, Hawaii, is keyed on/off in periodic sequences, and that same periodicity is observed on the subionospherically propagating probe signal generated by the 24.8 kHz transmitter NLK of Jim Creek, Washington. Previous initial conclusions published for these experiments do not hold under detailed review due to the lack of discernible onset delay and lag time in the observed perturbations, which eliminates transmitter-induced precipitation of electron radiation as a possible cause. Detailed testing of the receiver shows instrumental cross-modulation to not be a concern in these observations. It is thus concluded that the observed perturbations, despite occurring on a probe signal pathway that is 1750 km away from NPM at its point of closest approach, are due to direct ionospheric heating by the keyed VLF transmitter NPM. Results indicate that the VLF transmitter may affect the overlying ionosphere over much larger lateral regions than previously believed.

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1. Introduction

[2] Very low frequency (VLF, 3–30 kHz) electromagnetic waves are effective at detecting conductivity changes in the nighttime D-region ionosphere. Several sources of D-region conductivity enhancements have been detected and analyzed via perturbations on subionospherically propagating VLF probe signals [e.g., *Inan et al.*, 1985; *Barr et al.*, 1985; *Inan and Carpenter*, 1987; *Inan*, 1990; *Inan et al.*, 2007]. VLF transmitters themselves may produce such conductivity enhancements through two separate effects.

[3] The first way VLF transmitters may produce D-region conductivity enhancements is through direct absorption of the transmitted VLF wave energy in the ionosphere. As the transmitted VLF waves propagate through the weakly ionized plasma of the D-region, collisional heating transfers energy from the waves to the plasma, heating the D-region, and enhancing ionization and conductivity. This direct heating of the lower ionosphere by VLF transmitters was first discussed from a theoretical point of view by *Galejs* [1972], and experimental evidence was first provided by *Inan* [1990] when the VLF analog of the ionospheric cross-modulation effect was observed. *Taranenko et al.* [1992] compared VLF to HF for heating of the lower ionosphere with a focus on ELF generation and found that VLF heating dominates over HF up to ~90 km altitude, a study extended by *Barr and Stubbe* [1992]. Work by *Inan et al.* [1992], *Rodriguez and Inan* [1994], and *Rodriguez et al.* [1994] provided observations of VLF transmitter heating effects on VLF probe signals, and the results were shown to be consistent with 3-D modeling of the VLF heating and probe signal propagation. *Rodriguez et al.* [1994] further demonstrated that VLF transmitters can cause substantial heating of the nighttime D-region overhead on a regular basis.

[4] The second way VLF transmitters may produce D-region conductivity enhancements is indirectly, through the induced precipitation of radiation belt electrons and the resultant secondary ionization in the ionosphere. While much of the radiated energy from VLF transmitters remains guided between the Earth and the ionosphere, a small portion leaks through the ionosphere into the magnetosphere where it can interact with geomagnetically trapped energetic electrons. This interaction can alter the motion of

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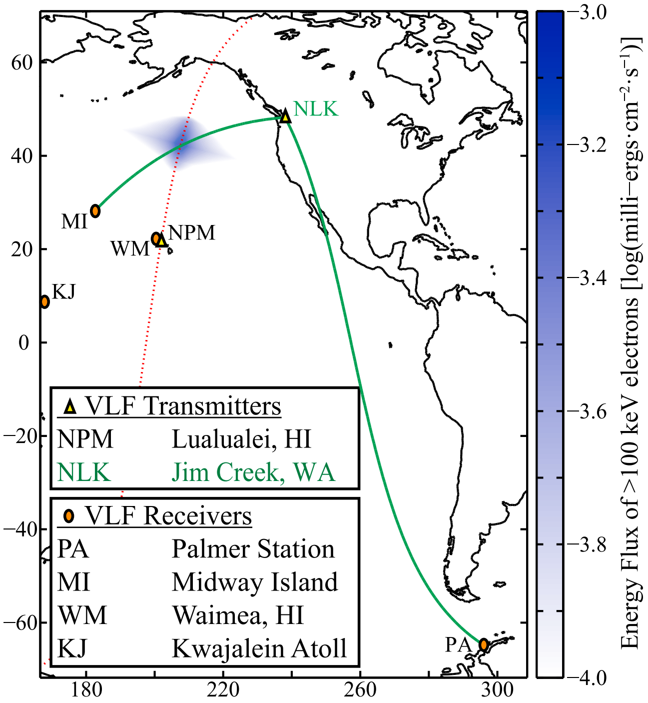

Figure 1. Map showing the subionospheric VLF detection network for the NPM keying experiments. The great circle paths from the NLK transmitter to the VLF receivers at Midway Island and Palmer Station are drawn in green. The dotted red line marks the magnetic longitude of NPM, and the theoretical precipitation region is shaded in blue, displaced north of NPM as calculated by the model of *Kulkarni et al.* [2008].

an energetic electron such that the formerly trapped electron precipitates into the upper atmosphere. As the precipitating energetic electrons impinge upon the upper atmosphere, resultant secondary ionization in the D-region causes conductivity enhancements that can perturb a subionospheric VLF probe signal. The capability of ground-based VLF transmitters to induce the precipitation of radiation belt electrons has been well established by satellite observations [*Vampola*, 1977; *Imhof*, 1983; *Koons et al.*, 1981], and modeling efforts have been made to better quantify the effects [*Abel and Thorne*, 1998; *Kulkarni et al.*, 2008]. While ground-based VLF remote sensing has been successfully applied to quantifying electron precipitation due to lightning [*Peter and Inan*, 2007; *Cotts et al.*, 2011, and references therein], the perturbations associated with VLF transmitter-induced electron precipitation have been considerably less distinct [*Inan et al.*, 2007].

[5] Two years of keying experiments were performed with the 21.4 kHz transmitter NPM in Lualualei, Hawaii, based on which both subionospheric [*Inan et al.*, 2007] and satellite-based [*Graf et al.*, 2009] observations have been reported. Upon initial analysis of a limited data set, *Inan et al.* [2007] concluded that the signature of transmitter-induced precipitation was present in the subionospheric VLF data. In the present paper, we revisit that subionospheric VLF data set and, upon more detailed analysis of a larger data set, conclude that the observed perturbations are incompatible with expectations for transmitter-induced precipitation and are more likely due to the extended heating effects of the keyed NPM transmitter.

2. Experimental Setup

[6] The U. S. Navy 400 kW, 21.4 kHz VLF transmitter NPM located in Lualualei, Hawaii (21.4°N, 158.2°W; $L = 1.17$), was keyed on/off in periodic formats for two 30 min periods on most days from 25 August 2005 through 2 April 2008. On some days, the two 30 min periods were placed back-to-back to create a single 60 min keying session. The majority of the transmissions utilized either a 0.1 Hz (5-sec on/5-sec off) or 0.2 Hz (3-sec on/2-sec off) periodic keying format. A 5-sec on/5-sec off format means NPM transmitted its 21.4 kHz signal at nearly full power for five seconds, then turned off for five seconds, and repeated this cycle for the duration of the 30 min keying period.

[7] Ground-based VLF measurements were recorded by two-channel VLF receivers installed in the Pacific at Midway Atoll (MI, 28.21°N, 177.38°W), Waimea, Hawaii (WM, 21.96°N, 159.67°W), Kwajalein Atoll (KJ, 8.72°N, 167.72°E), and in the Antarctic at Palmer Station (PA, 64.77°S, 64.05°W). These receivers are similar to the Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education (AWESOME) instrument described by *Cohen et al.* [2010]. Each antenna is an air-core, wire-loop antenna for detecting the magnetic field, and each receiver possesses two antennas: one oriented north-south, and one oriented east-west. Data is recorded at 100 kHz sampling rate with 16-bits per sample. The amplitude and phase of narrowband signals at specific frequencies are demodulated and recorded at 50 Hz. Each station receives subionospherically propagating narrowband signals from many VLF transmitters. The most pertinent VLF transmitters for this study are the keyed transmitter NPM, as well as the additional U. S. Navy transmitter NLK (24.8 kHz, 200 kW; 48.20°N, 121.92°W). The transmitter NLK provides a continuous probe signal for measuring ionospheric perturbations along the great circle path from transmitter to receiver. The geographic locations of these stations are shown in Figure 1 together with a theoretical precipitation flux induced by the NPM transmitter as computed by the model of *Kulkarni et al.* [2008]. For the NPM transmitter, which is located at $L = 1.17$, the precipitation region is expected to be displaced to the north of the transmitter for nonducted magnetospheric propagation [*Inan et al.*, 2007]. To reduce clutter, only the great circle paths of two select probe signal pathways are included on the map: NLK to Midway and NLK to Palmer.

3. Observations

[8] In order to detect the potentially weak periodic perturbations of the ionosphere induced by the keyed NPM transmitter, *Inan et al.* [2007] utilized both superposed epoch and time-integrated Fourier analysis to analyze the received VLF probe signals at each VLF receiver station for the available NPM keying sessions. The key parameters for determining the cause of VLF probe signal perturbations are the onset delay and lag of the periodic perturbations with respect to the keyed transmitter signal. We define "onset delay" to be the time delay, within a keying period, from

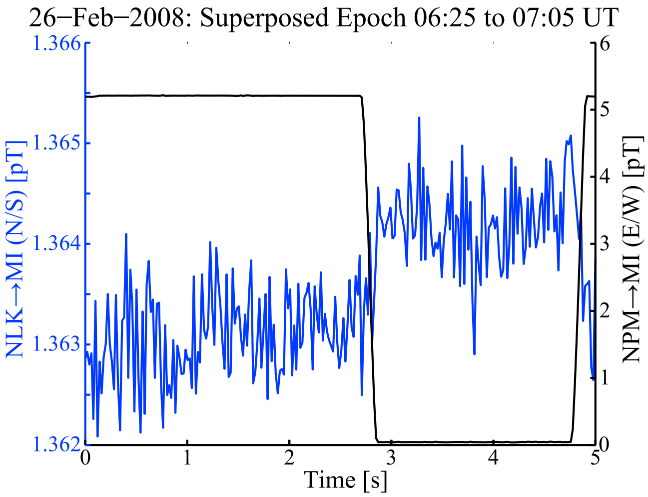

Figure 2. Superposed epoch of the NLK and NPM signals received at Midway (MI), generated from 40 min of data recorded during the keying session of 26 February 2008. The NPM signal in black is keyed in a 0.2 Hz (3-sec on/2-sec off) periodic format. Aperturbation of the same periodicity and no relative onset delay is seen in the NLK probe signal plotted in blue.

when the NPM transmitter switches on to when a perturbation begins to appear on the probe signal. The "lag" is the time delay, over many keying periods, from when NPM begins its on/off keying for the day to when a perturbation begins to appear on the probe signal. Since onset delay is critical in determining the cause of the perturbation, we focus our attention only on superposed epoch analysis. The signal-to-noise ratio in the initial superposed epoch analysis of *Inan et al.* [2007] prevented the determination of the presence or absence of an onset delay. In this paper, we remove impulsive noise prior to computing the superposed epoch to greatly increase the signal-to-noise ratio. Any impulsive noise (defined as at least one standard-deviation above the local 3-second median) of less than half a second in duration is replaced by the local mean of the data. Much of the impulsive noise in VLF receiver data is caused by sferics (the electromagnetic impulse from lightning discharges), and the processing to remove sferics should not affect our time resolution or the presence of the small periodic perturbations we aim to detect.

[9] The superposed epoch of the NLK probe signal amplitude as received at Midway on 26 February 2008 is plotted in Figure 2. During this 40 min portion of a 60 min keying session, the NPM transmitter is keyed in a 0.2 Hz (3-sec on/2-sec off) periodic format. The NPM signal in this plot clearly shows the on/off keying format, with NPM being on for approximately the first three seconds of each epoch, and off for the final two seconds. The NLK signal shows a distinct amplitude decrease when NPM is on. To confirm that such a periodicity was not inherent in the NLK signal at this time, the superposed epoch was also computed for the 30 min prior to and following this keying session, and no such 0.2 Hz periodicity was observed in the signal at those times. Similar results are achieved on this NLK probe signal on a regular basis, from keying sessions of 0.05 Hz, 0.1 Hz, 0.2 Hz, and 0.5 Hz periodicity over the course of the NPM keying experiments.

[10] The removal of impulsive noise prior to averaging is the primary reason why this perturbation appears significantly more distinct here than in the similar case published by *Inan et al.* [2007, Figure 2]. The perturbation is still very small ($\Delta A \simeq -0.006$ dB compared to $\Delta A \simeq -0.012$ dB reported by *Inan et al.* [2007]), but the noise fluctuations superposed on the averaged probe signal has been significantly reduced. With the perturbation now appearing distinctly, it is clear that there is no discernible onset delay from when NPM turns on to when the perturbation appears on the NLK probe signal. Likewise, there is no discernible delay between NPM turning off and the disappearance of the perturbation. This lack of onset delay indicates that the perturbation is not caused by NPM-induced electron precipitation since a delay of at least a quarter of a second is to be expected based simply on the kinematics of the interaction (i.e., the travel time of the wave to the equatorial interactions region and the travel time of the scattered electrons from there to the ionosphere). The time resolution of the superposed epoch data is 20 milliseconds.

[11] In addition to the results from Midway in the Pacific analyzed for NPM-induced precipitation in the local bounce loss cone, *Inan et al.* [2007] also presented results from Palmer Station in Antarctica for detection of NPM-induced precipitation in the drift loss cone. A series of superposed epochs of the NLK probe signal amplitude as received at Palmer on 14 January 2008 is plotted in Figure 3 (comparable to *Inan et al.* [2007, Figure 3]). During the removal of impulsive noise for this data set, each signal is also processed with a 220 millisecond running-median filter. This processing is necessary to further reduce the impulsive noise in this case, due to the need to determine the presence of a very small perturbation, but it also lowers the time resolution with which we can specify an onset delay. The six plots presented are all for the same 08:15–08:45 UT NPM keying session, but the averaging window for each superposed epoch is taken to be only 15 min and is gradually shifted through that 30 min keying session in 10 min steps. The first plot averages 15 min of data entirely before the NPM keying session has begun, the second plot averages 15 min of data for which only 10 min includes NPM keying, the third plot is entirely within the NPM keying session, and so on out through the tail end of the keying session. Outside of the keying session (the first and last plots) the NLK signal has a consistent amplitude of ~28 dB with no inherent 0.1 Hz periodicity.

[12] Figures 3c and 3d can be analyzed much like Figure 2. Again, there is a distinct amplitude perturbation on the probe signal when NPM is on (this time the perturbation is negative). Also, while our effective time resolution has been lowered in this case, there is nevertheless no discernible onset delay between NPM turning on and the NLK probe signal being perturbed. The added detail provided by the series of plots is that there is no significant lag between the beginning of the NPM keying session at 08:15 UT and the appearance of the perturbation on the NLK probe signal. The perturbation looks to be present already in the second plot which overlaps with the first 10 min of the NPM keying session. While it is not presented here, a more thorough analysis involving additional window sizes and smaller steps

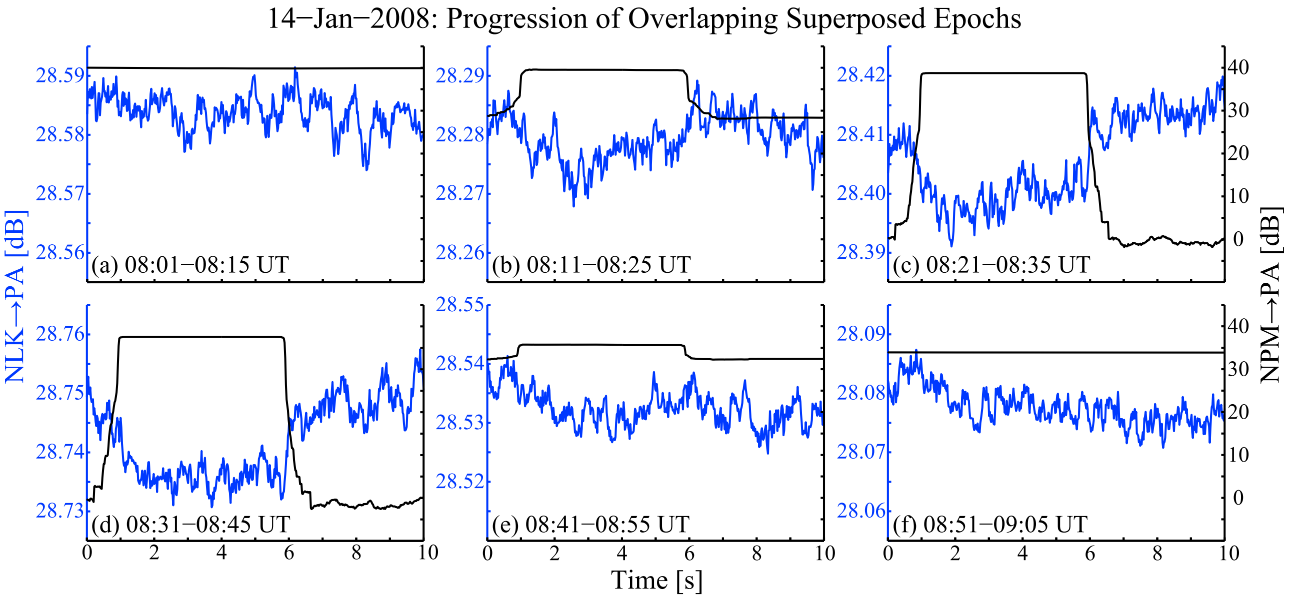

Figure 3. Progressive superposed epochs of NLK and NPM signals received at Palmer (PA) on 14 January 2008. The averaging window for each superposed epoch plot is taken to be only 15 min, and that window is gradually shifted through the 30 min keying session in 10 min steps to create these six sequential plots. The NPM signal in black is keyed in a 0.1 Hz (5-sec on/5-sec off) periodic format from 08:15–08:45 UT. A perturbation of the same periodicity and no relative lag or onset delay is seen in the NLK probe signal plotted in blue.

than 10 min suggests that there is no discernible lag between the beginning of the NPM keying session and the appearance of the perturbations on the NLK to Palmer probe signal.

4. Discussion

[13] The NPM transmitter is keyed periodically for up to 30 min to an hour, and that same periodicity is observed on a probe VLF signal. As described above, the two possible physical causes of such an observed periodicity in the probe signal are direct heating of the lower ionosphere by NPM and induced electron precipitation by NPM. A third possible cause could be instrumental, that is, signal cross-modulation due to nonlinearities within the VLF receiver. *Inan et al.* [2007] presented results similar to the two cases shown here and suggested that the perturbations were due to transmitter-induced electron precipitation. The effects of ionospheric heating were ruled out at the time due to the >1000 km distance between the NPM transmitter and the signal path of NLK to Midway with references to theoretical results of *Rodriguez* [1994]. Cross-modulation within the receiver was ruled out on grounds that the perturbation did not appear on other VLF signals not passing through the heating or precipitation regions. Unfortunately, due to a lack of the sferic removal analysis technique prior to averaging by *Inan et al.* [2007], the specification of onset delays and lag times in their observations was not possible.

[14] Now that the onset delays and lag times are more discernible, the observations are not consistent with NPM-induced precipitation as the cause of the perturbation. There is no observable onset delay greater than our time resolution in either case (~50 milliseconds in the Midway observations of Figure 2, ~220 milliseconds in the Palmer observations of Figure 3). It would take at least a quarter of a second to half a second for the VLF radiation from NPM to propagate to the magnetospheric equatorial plane, interact with and scatter trapped radiation, the scattered energetic electrons to subsequently travel down to the ionosphere and precipitate, and for the resultant secondary ionization in the upper atmosphere to perturb the probe signal. Therefore, transmitter induced precipitation cannot be the cause of the perturbations on the VLF probe signal for the Midway observations.

[15] Since the observed perturbations cannot be attributed to transmitter-induced electron precipitation, we should revisit the theoretical analysis of *Inan et al.* [2007] which suggests the effects of NPM-induced electron precipitation would be detectable on the NLK to Midway probe signal. Even in the presence of a perturbation due to heating or instrumental cross-modulation, a second, delayed perturbation could be present due to the effects of transmitter-induced electron precipitation. Such a delayed perturbation, however, is never observed. Since the modeling and analysis of *Inan et al.* [2007] and *Starks et al.* [2008] has shown that many previous models overestimated the nighttime trans-ionospheric propagation of VLF transmitter signals by about 20 dB. Much of this previous work, including that of *Inan et al.* [2007], utilized the ionospheric absorption curves of *Helliwell* [1965, Figure 3–35] to estimate the VLF signal strengths penetrating into the magnetosphere. These were the best available estimates at the time, and were in agreement with several models, but satellite observations have since shown them to be gross overestimates. So, even with overestimating the VLF signal strength by 20 dB and assuming a square pitch angle distribution for the trapped particle population, the modeling of *Inan et al.* [2007] for the detection of NPM-induced electron precipitation predicts a

perturbation on the NLK probe signal that would be just barely detectable. Given this, we would not expect the effects of transmitter-induced particle precipitation to be observable in these NPM experiments.

[16] The absence of a lag between the beginning of the NPM keying session and the appearance of perturbations on the NLK to Palmer probe signal is inconsistent with NPM-induced drift loss cone precipitation as the cause. The NLK to Palmer signal pathway passes through the South Atlantic Anomaly (SAA) where drift loss cone particles precipitate. *Inan et al.* [2007] argued that the keyed NPM transmitter periodically scattered electrons into the drift loss cone. These electrons would drift eastward and precipitate in the SAA several minutes later, perturbing a probe signal in that region with the NPM keying periodicity. The time for 100 keV electrons to drift from the geomagnetic longitude of NPM to that of the NLK-Palmer path near the SAA is at least 13 min. Therefore, you would expect a lag time of several minutes before the perturbations appear on this NLK to Palmer probe signal if induced drift loss cone precipitation were the cause. Since no such lag is observed, we conclude that this type of drift loss cone precipitation cannot be the cause. There is still the possibility that longitudinal spreading of the NPM signal could induce precipitation of particles trapped closer to the SAA so that little to no drifting or lag would be required before effecting a perturbation on the probe signal, but, given how small of an effect we already expect for induced precipitation at the longitude of NPM, we would not expect an effect at this more distant longitude to be any more detectable. Additionally, while the processing of the Palmer signal changed its time resolution from ~50 ms to ~220 ms, the lack of any observable onset delay still suggests that the cause of these perturbation is likely not induced precipitation.

[17] In summary, since there is no discernible onset delay or lag time, we conclude the observed perturbations are not due to NPM-induced electron precipitation. It should also be noted that *Inan et al.* [2007] found no correlation between the observations and the *Kp* or *Dst* geomagnetic indices. Since the trapped particle population is dependent on geomagnetic activity, and induced precipitation is dependent on the trapped particle population, this lack of correlation with the geomagnetic indices further suggests that induced precipitation is unlikely to be the cause of the observed perturbations.

[18] In addition to the Midway and Palmer sites discussed here, *Inan et al.* [2007] also mentioned observations at Waimea and Kwajalein in the Pacific region. *Inan et al.* [2007] stated that Waimea was too close to NPM to be used for the detection of transmitter-induced precipitation, and that Kwajalein data was too inconsistent and with too low signal to noise levels to show any evidence of detection. Additionally, due to the limited operation of the Waimea and Kwajalein sites, data is only available from these locations for the first few months of the NPM keying experiments. Analysis of the available Waimea and Kwajalein data sets using the sferic removal technique applied in this paper does little to change these statements of *Inan et al.* [2007]. Waimea is very close to the NPM transmitter and its data consistently shows a strong perturbation similar to that presented in Figure 2 for Midway. The absence of an onset delay in the Waimea data is very clear. Kwajalein data is less useful for these studies due to weaker probe signal strengths at that location, higher local noise levels, and the frequent prevelance of strong sferics in the vicinity. While some periodic perturbations have now been discovered on the probe signals at Kwajalein, and no onset delay is evident in those observations, the low signal to noise levels and the infrequency of the detections limits the conclusions that can be drawn.

[19] We have eliminated transmitter-induced precipitation as a possible cause of the observed perturbations, thus leaving instrumental cross-modulation and direct heating of the lower ionosphere as the remaining options. Instrumental cross-modulation in the VLF receiver is unlikely to be the cause due to the lack of a perturbation on certain VLF signals not passing near the heating region of the keyed VLF transmitter. In the NPM (21.4 kHz) experiments, for example, the periodic perturbation is often observed on the NLK (24.8 kHz) signal at Midway receiver, but not on the JJI (22.2 kHz) signal. The JJI signal originates in Japan, so it is less likely to experience a perturbation from any NPM-induced ionospheric perturbation. The frequency of JJI is closer to that of NPM, and its received power is similar to that of NLK, so cross-modulation would be more likely. The fact that a perturbation is observed on NLK and not JJI means cross-modulation is unlikely to be the cause. A similar argument can be made for data received at Palmer, just using the 25.2 kHz NLM or 24.0 kHz NAA in place of JJI. That argument is less definitive, however, because NPM and NLK are the two strongest signals received at Palmer during the keying experiments, with NLM and NAA being the next strongest at only about half the amplitude of NLK on average.

[20] To definitively verify that cross-modulation within the receiver is not producing the observed perturbations, the VLF receiver that was deployed at Midway during the keying experiments was brought to Stanford and thoroughly tested. Test signals were injected into the Midway receiver to mimic the observations of Figure 2. With the antenna disconnected and a dummy loop installed in its place, test signals of 21.4 kHz (TS1) and 24.8 kHz (TS2) were injected into the dummy loop. Amplitudes were tuned to recreate the signal levels observed in the experiment, and the 21.4 kHz signal was keyed in a 1-sec on/2-sec off periodic format for two hours while the 24.8 kHz signal was left as a constant tone. Since the receiver has two channels (one north-south and one east-west), and the NPM transmitter signal is observed on both channels with differing amplitudes, the larger of these observed signal strengths was simply injected into both channels of the receiver during the test. This conservative test should increase the possibility of cross-modulation within the receiver and thus constitutes a thorough test. The results of this cross-modulation test are presented in Figure 4, where the *y*-axis scales are set to be the same as those of Figure 2. While the 24.8 kHz NLK signal exhibited a perturbation of ~1 fT during the NPM experiments, the 24.8 kHz test signal TS2 exhibits no such perturbation in our tests. We conclude that the observed perturbations at Midway during the NPM keying experiments are not due to cross-modulation within the receiver. This test does not completely rule out the possibility of cross-modulation at Palmer, unfortunately, as a different

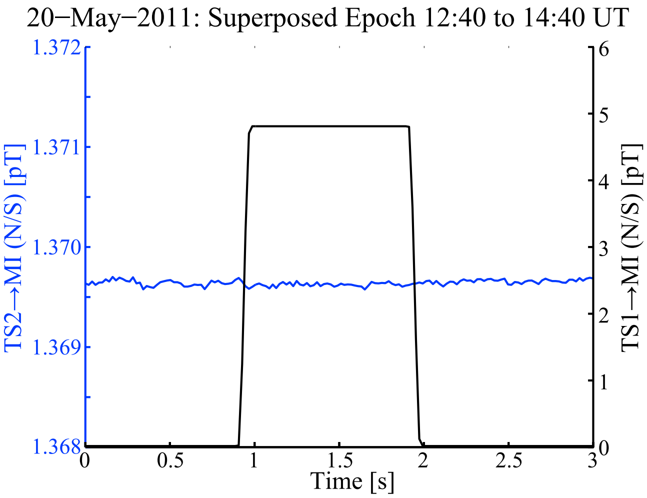

Figure 4. Superposed epoch results of cross-modulation test executed on the Midway (MI) receiver. Signals TS1 and TS2 are injected from a function generator with their amplitude and frequency set to mimic the NPM and NLK signals received at Midway on 26 February 2008. The 21.4 kHz TS1 plotted in black is keyed in a 1-sec on/2-sec off periodic format for two hours, and no significant perturbation of this periodicity is observed in the 24.8 kHz TS2 plotted in blue.

receiver model is installed there, and that receiver is not available for laboratory testing at this time.

[21] Through eliminating the other possible causes of the observed VLF probe signal perturbations, we conclude that direct heating of the lower ionosphere by NPM is the most likely cause. The lack of onset delay and/or lag (depending on the experimental setup) between the periodic perturbations on the VLF probe signal and the keyed VLF transmitter eliminates transmitter-induced precipitation as a possible cause, contrary to the suggestions of *Inan et al.* [2007]. Extensive testing of the VLF receiver system used in the experiment eliminates instrumental cross-modulation as a possible cause. With transmitter-induced precipitation and instrumental cross-modulation eliminated, we conclude that direct heating of the lower ionosphere by NPM is the most likely cause of the observed VLF probe signal perturbations. This finding suggests that the effects of ionospheric heating by powerful VLF transmitters are detectable over very long distances. *Rodriguez et al.* [1994] detected such perturbations in cases when the distance from the heating transmitter to the closest approach of the probe signal pathway was up to 770 km, and those observations were taken from single on/off events without the benefit of any periodic keying for superposed epoch analysis. In this connection, observation of the effects of ionospheric heating induced by NPM on the NLK to Midway probe signal pathway at 1750 km distance is perhaps to be expected considering the fact that averaging over many cycles of on/off keying brings out substantial improvement in signal-to-noise ratio. Observing the effects on the NLK to Palmer probe signal 4360 km away from the NPM transmitter may seem unlikely at first, but it may well be feasible when the extended lateral ionospheric heating of the subionospherically propagating NPM signal is taken into account. Since a 20 kHz signal will propagate in the nighttime Earth-ionosphere waveguide with only ~2 dB/Mm of attenuation at great distances [*Davies*, 1990, p. 387], the NPM signal strength at 4360 km would only be ~5 dB less than its strength at 1750 km. Keying experiments have also taken place using VLF transmitters NAA (24.0 kHz, 885 kW; 44.65°N, 67.28°W) and NWC (19.8 kHz, 1 MW; 21.82°S, 114.17°E), so future work will focus on characterizing the lateral extent of ionospheric heating regions overhead VLF transmitters.

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