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Is magnetospheric line radiation man-made?

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Abstract. Magnetospheric line radiation (MLR) events are relatively narrowband VLF signals (~30 Hz) that sometimes drift in frequency and that have been observed in both ground-based and satellite data sets. We present the result of a survey undertaken on the basis of measurements made of MLR events observed at Halley station, Antarctica (75°35'S, 26°33'W, $L \approx 4.3$) during June, July, September, and December 1995, specifically to examine whether there is a link between MLR and power line harmonic radiation (PLHR). We find that (1) the diurnal variation of MLR occurrence at Halley does not resemble the expected load pattern in the industrialized conjugate hemisphere; (2) MLR does not show the pronounced east-west asymmetry in the distribution of arrival directions which would be the case if it was linked to North American electrical load; (3) MLR does not show an immediate association with geomagnetic activity, as would be expected from increases in PLHR levels produced by geomagnetically-induced currents saturating transformers; and (4) there is no evidence of a Sunday, weekend, or other 7-day cycle in the occurrence of MLR. Taken together these results strongly suggest that MLR is a natural VLF emission and is not primarily caused by PLHR. In addition, Halley data have been examined to determine whether the intensity of all types of VLF emissions are influenced by PLHR. We find that (1) there is no significant difference between weekdays and weekends over the frequency range 0.5-9.3 kHz and (2) there is no consistent change in wave intensity that is observed around any of the major North American holiday periods. It is concluded that PLHR is not a significant influence on geospace as viewed from Halley.

1. Introduction

The first report of magnetospheric line radiation (MLR) came from observations made by ground-based receivers at Siple, Antarctica, and Roberval, Québec [*Helliwell et al.*, 1975]. On frequency spectrograms these lines formed parallel tracks with frequencies in the range 2-5 kHz and widths of ~30 Hz, with some showing separations ~120 Hz. The majority of the lines were constant in frequency (within the measurement uncertainty of 5-10 Hz), but in a small number of cases they drifted up or down in frequency together, in one case as fast as 50 Hz min^{-1}. The authors suggested that these lines might be caused by power line harmonic radiation (PLHR), harmonics emitted from long power lines of the Canadian 60-Hz electricity mains transmission system and radiated upward into the ionosphere and magnetosphere. It was postulated that PLHR could propagate in the magnetosphere in the whistler mode, where it might be amplified by wave-particle interactions and alter near-Earth geospace. PLHR could act as the "seed", interacting nonlinearly with trapped particles to produce magnetospheric line radiation. Evidence for the power line harmonic generation mechanism of MLR included observations at Roberval of entrainment of transmitter-induced VLF emissions by local induction line harmonics of 60 Hz. The emissions commonly varied freely in frequency by many hundreds of Hertz over a few seconds and then on encountering a particular local harmonic were entrained, cut off, or had the slope of their frequency variation reversed [*Helliwell et al.*, 1975]. The temporal (diurnal) variation of MLR occurrence shows some similarities to the electrical load in the industrialized conjugate region [*Park and Helliwell*, 1978].

While most electrical systems worldwide have nominal power system frequencies of 50 or 60 Hz, slight distortions in the electrical waveform produces harmonics of the fundamental. In most areas of the United States the voltage found on transmission systems typically has much less than 1% distortion [*Dugan et al.*, 1996]. However, problems associated with harmonic distortion of the electrical supply have been significant since the very beginning of the electric power industry [*Owen*, 1998]. Harmonic distortion can lead to significant heating in transformers and electric motors [*Dugan et al.*, 1996] and has also caused interference in telecommunications systems [*Robinson*, 1966]. Because of the increasingly common use of nonlinear electronic devices, the level of harmonic distortion may increase substantially in the near future [*Stebbins*, 1996].

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The association between PLHR and MLR has recently been questioned by the largest survey to date of MLR line frequency spacings, undertaken using observations from Halley station, Antarctica (75°35'S, 26°33'W, $L \approx 4.3$) [*Rodger et al.*, 1999, 2000]. In a 2-week period in June 1995, 128 MLR events were observed containing 698 distinct MLR lines. MLR was present in 7.0% of the minute-long VLF recordings. There was a wide range of line spacings which did not preferentially show spacings near harmonics of electrical transmission frequencies, either 50 or 60 Hz. The distribution of MLR line spacings observed had a roughly exponential form, which the authors concluded was suggestive of a different mechanism for MLR than PLHR. Previously, a study making use of ISIS satellite data found that neither the initial frequencies of 42 MLR lines nor the frequency spacings between the lines were multiples of 50 or 60 Hz [*Rodger et al.*, 1995], although the AUREOL-3 satellite detected 32 MLR distinct lines which were all separated by 50 Hz [*Parrot*, 1994]. The temporal properties of MLR have been recently presented by *Rodger et al.* [2000].

MLR and the more general questions and observations associated with PLHR are discussed in detail in the reviews of *Bullough* [1995] and *Parrot and Zaslavski* [1996]. We should note that there have been instances where the term PLHR (or sometimes "power line radiation" (PLR)) is used to describe the VLF line radiation which we refer to as MLR. Given that the association between PLHR and MLR is still uncertain, we use PLHR to refer only to the harmonic fields produced by the local electrical supply which are radiated into the Earth-ionosphere waveguide, ionosphere, and magnetosphere. It is uncertain whether PLHR has been observed in the magnetosphere, although "tram line" events characterized by narrow bandwidth and zero frequency drift and with frequencies and spacings that are 50 or 60 Hz harmonics [*Rodger et al.*, 1995] might qualify. This may also be the case with satellite measurements made over Japan of increases in the magnetic field strength at the 50- and 60-Hz fundamental frequencies (the Japanese commercial power system is divided into two regions with roughly half the country at 50 Hz and the other half at 60 Hz) [*Tomizawa and Yoshino*, 1985].

PLHR might make a significant contribution to the formation of the "electron slot" between the inner and outer radiation belts (around $2 \leq L \leq 3$) [*Bullough et al.*, 1976], influence the occurrence and starting frequency of magnetospheric chorus elements [*Luette et al.*, 1977, 1979], and interact with whistlers to produce monochromatic whistler precursors [*Park and Helliwell*, 1977]. Others have failed to find the geographic or frequency dependence in chorus activity [*Tsurutani et al.*, 1979; *Thorne and Tsurutani*, 1979] and have shown that the starting frequencies of monochromatic whistler precursors are randomly distributed. Electron precipitation caused by PLHR might explain a reported increase in thunderstorm occurrence in southern Canada (*Changnon* [1977] as referenced by *Bullough et al.* [1985]). Perhaps a more clear PLHR effect is the temporarily "capture" or entrainment of magnetospheric triggered emissions at induction line frequencies, showing that PLHR can sometimes directly affect magnetospheric processes [*Nunn et al.*, 1999]. The same data appear to show chorus and periodic emissions which are triggered at PLHR frequencies, as previously reported by some authors [see *Nunn et al.*, 1999, and references therein].

In this paper we report on a survey of MLR activity in June, July, September, and December 1995. This data set was previously used to examine the temporal properties of Halley MLR events [*Rodger et al.*, 2000], and a limited part of the data set has been examined previously to measure the frequency, spacing, drift, and intensity of MLR lines [*Rodger et al.*, 1999]. In this paper we examine the suggested link between MLR and PLHR. We take an MLR event to refer to the presence of MLR line activity for some part of a minute-long recording. We analyze VLF recordings made at Halley, Antarctica. Having considered the links between MLR and PLHR, we go on to consider the significance of PLHR to the levels of wave activity at Halley.

2. VLF Database and Experimental Procedure

Wideband ELF/VLF (0.3 to ~22 kHz) observations have been made at Halley using two vertical single-turn 56-m^2 loop antennae, signals from which have been amplified by twin low-noise preamplifiers. The aerials and preamplifiers are located sufficiently distant (1.8 km) from Halley station that locally generated electromagnetic noise is negligible over the whole frequency range. Sensitivity (typically ~10^{-31} T^2 Hz^{-1} at 5 kHz) is normally limited by global thunderstorm noise (sferics) rather than by receiver system noise. Calibration is achieved by simulating a signal of known intensity, frequency, and arrival direction. Five frequency calibration tones (488, 977, 1953, 3906, and 7813 Hz) are injected into the data once a minute, at the beginning of the minute [*Smith*, 1995]. Recordings are normally made for 1 min every 15 min (5-6, 20-21, 35-36, and 50-51 min past the hour). At times of unusual activity or for special campaigns, alternative schedules of 1-min recording every 5 min, or continuous recording, have been undertaken. Time code (IRIG-B) is simultaneously recorded with the data onto digital audio tapes (DAT). Control of the tape recorders is through the Advanced VLF Data Analysis System (AVDAS) [*Smith et al.*, 1994], which is also used for data analysis. VLF observations at Halley are particularly well suited to the examination of the PLHR/MLR question; local power consumption is low, while the geomagnetic conjugate of this station is near the eastern seaboard of the continental United States of America, a region of high electrical power use and therefore probably a powerful source of PLHR.

The search for MLR events in the Halley ELF/VLF data has been undertaken using the AVDAS routine MLRSCAN. This routine is used for digitizing and analyzing MLR events in our recordings. The MLRSCAN routine used in conjunction with AVDAS produces 0- to 5-kHz spectra with 12.5-Hz frequency resolution averaged every 500 ms. These spectra were examined visually for MLR events. The averaging process tends to emphasize MLR events, drawing them out from the background activity. Examples of MLR events observed in the MLRSCAN data format were shown in Plate 1 of *Rodger et al.* [1999].

In this study we restrict ourselves to the analysis of Halley ELF/VLF data collected in the months of June, July, September, and December 1995. Inside this time window there were 15,281 complete minutes of Halley wideband ELF/VLF data recorded, all of which were examined for MLR activity, producing 863 MLR events. However, as has been reported in previous studies [e.g., *Rodger et al.*, 2000], MLR tends to be associated with other VLF wave activity (e.g., chorus and hiss). As noted above, at these times a higher recording rate was often used, which could lead to bias in the examination of temporal properties. For this reason we limit ourselves to including only those minutes which were recorded at the 1:15 min schedule, as outlined above. Under this constraint our data set contains 477 MLR events observed in 11,448 min of 1:15 min recordings (thus with an average occurrence rate of ~4.2%). An MLR event refers to the presence of MLR line activity for some part of a minute-long recording. It should be noted that there is no universally agreed definition of what qualifies as the presence of MLR. As such, MLR identification is subjective, the criteria used for selecting an MLR event are that at least one well-defined line should be visible on the spectrogram and that these lines exhibit characteristics which distinguish them from locally produced induction lines (e.g., the bandwidth of Halley induction lines is <1 Hz whereas MLR bandwidths are generally 30-40 Hz [*Rodger et al.,* 1999]) The same identification criteria was used by *Rodger et al.* [1999, 2000]. In all of these studies, frequency spacing is only measured when the MLR event contains multiple lines.

3. Properties of MLR and Relation With PLHR

In this section we examine experimental observations from Halley to test whether MLR is linked to the presence or properties of PLHR. A number of different approaches are taken to consider this question: the frequency spacing of MLR lines (section 3.1), variation in diurnal occurrence (section 3.2), the bearing of MLR events (section 3.3), their association with geomagnetic activity (section 3.4), and searching for a "Sunday effect" in MLR occurrence where the 7-day cycle used by humankind might be linked to MLR through changing PLHR (section 3.5). Having considered the links between MLR and PLHR, we go on to consider the significance of PLHR to the levels of wave nactivity at Halley through the Sunday effect (section 3.6) and through possible links with North American holidays (section 3.7), neither of which has been previously examined at Halley.

3.1. Spacing of MLR

The examination of the frequency spacing between MLR lines is central to the question of whether or not MLR is created by PLHR. The largest study of MLR line spacing to date found that there was a wide range of spacings which did not preferentially show spacings near harmonics of electrical transmission frequencies, either 50 or 60 Hz [*Rodger et al.*, 1999]. More recently, case studies using 2.5-Hz frequency resolution have shown that single lines seen in the 0- to 5-kHz spectra can be made up of multiple (two to three) lines with widths of 5-10 Hz and with smaller spacings (as small as <10 Hz) [see *Rodger et al.*, 2000, Figure 1]. These studies concluded that the spacings do not support a PLHR-driven mechanism for MLR production.

3.2. Diurnal Variation in MLR occurrence

The diurnal variation of Halley MLR events is shown in Figure 1, using the same data as those used by *Rodger et al.* [2000]. In the previous study we interpreted the twin-peaked distribution (maxima at ~0600 UT (0400 LT at Halley) and ~1900 UT (1700 LT)) as probably due to an association of MLR with a combination of chorus and midlatitude hiss. The timing of the twin-peaked distribution MLR occurrence is consistent with the natural diurnal variation of these wave phenomena. The sharp decrease in MLR observations at ~10 LT is believed to be a consequence of this diurnal variation and is not due to bias in the LT variation of observations. In this paper we consider for the first time possible similarities (or otherwise) between the temporal variation of MLR occurrence at Halley and electrical load in the industrialized conjugate region.

Figure 2 shows the diurnal variation in the hourly normalized electrical load for New Zealand [*Rodger et al.*, 1995], Newfoundland Island in 1980, Hydro Québec [*Park and Helliwell*, 1978], the South Atlantic region of the United States [*Hutzler*, 1999], Texas (data provided by M. Zehani, Dataphase, 1998), and Israel [*Einav*, 1996]. In order to compare our MLR occurrence with electrical use, we follow the practice of *Park and Helliwell* [1978] and assume that the occurrence is dominated by generation in the conjugate hemisphere. The conjugate of Halley is near Newfoundland, Canada. It has not proved possible to gain access to load curves for Newfoundland and Labrador Hydro for the times in 1995 when our observations were made at Halley. However, we note that the general shape of all the load curves shown in Figure 2 are similar, even though the load curves span ~20 years (from New Zealand in the late seventies to Texas in 1998). While the amount of power consumed in Newfoundland will certainly have increased over the ~15 years between the load curve and our observations, the shape is unlikely to have altered significantly.

The predominant peaks in the MLR data occur at ~0300 and 1600 LT at Newfoundland (which is 1 hour behind Halley LT). Newfoundland local time is similar to that of the highly industrialized northeast of the United States, which might also be expected to contribute to the PLHR levels in the conjugate region. None of the load curves shown in Figure 2 provide a good comparison with the MLR occurrence shifted into Newfoundland local time. In fact, the first peak in Figure 1 (~0300 LT) corresponds approximately to the time when electrical load is likely to have been lowest in Newfoundland. Figure 1 shows a roughly equal proportion of MLR occurrence between day and night. This would not be expected for a ground-based (e.g., PLHR) source in the Northern Hemisphere, which would be strongly influenced by the differing ionospheric absorption between day and night. Many of the

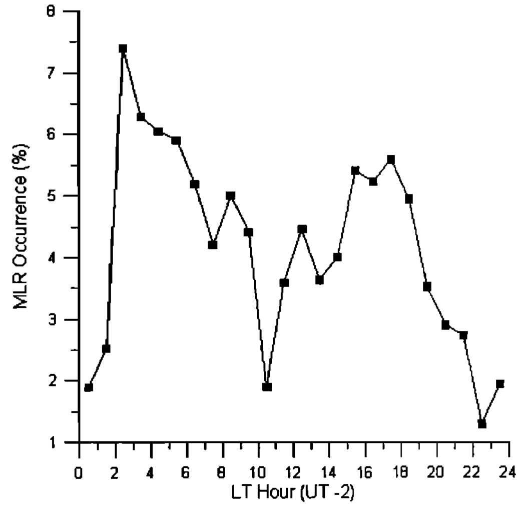

Figure 1. The diurnal variation in magnetospheric line radiation occurrence at Halley by LT hour normalized by the number of VLF recordings that were searched for MLR activity [after *Rodger et al.*, 2000].

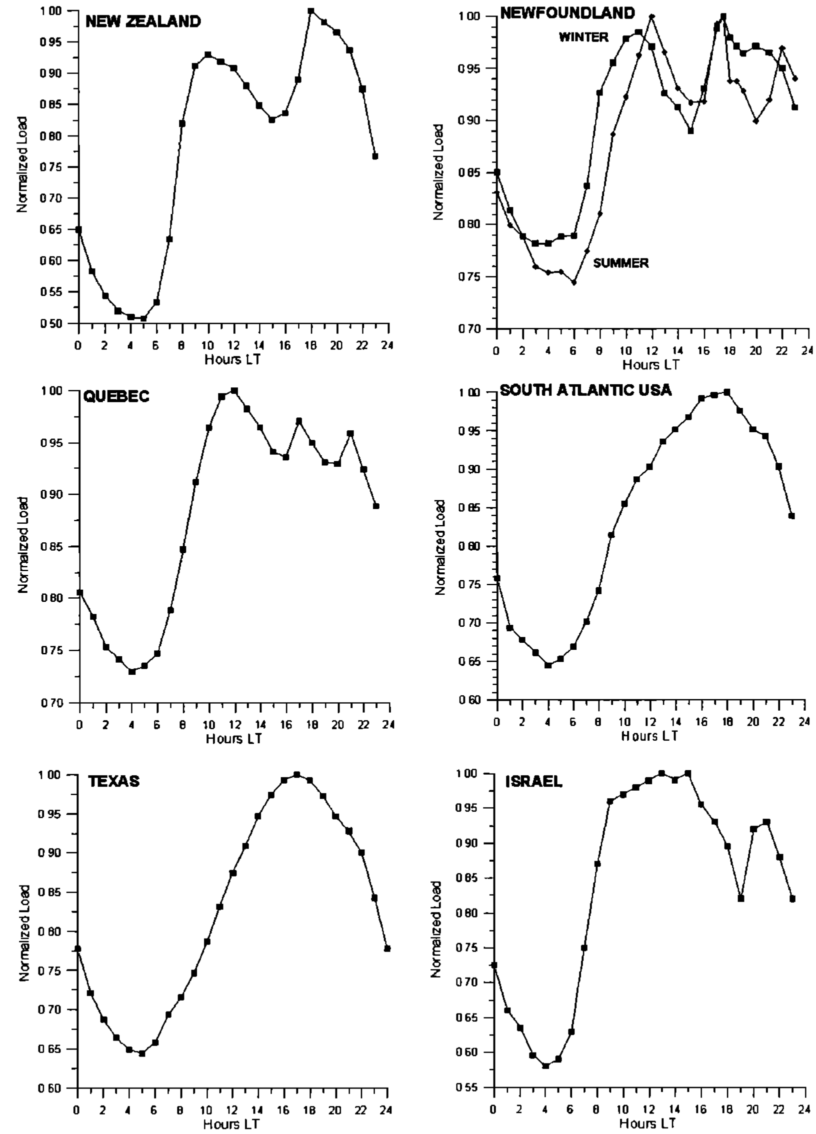

Figure 2. Local time variation in the normalized electrical power demand (load) in various countries (normalized to the peak of the diurnal load). See text for sources.

load curves shown in Figure 2 also have a secondary minimum near ~1600 LT which is not apparent in Figure 1. Thus there does not appear to be any similarities between the electrical load in the industrialized region conjugate to Halley and MLR occurrence in our data set.

3.3. Directionality of MLR

Halley is well suited to examine the PLHR/MLR question in a manner not previously considered. As noted in section 3.2, the conjugate of Halley is the eastern seaboard of North America, potentially a powerful source of PLHR. PLHR levels to the east of North America are likely to be very low; this region is dominated by the Atlantic Ocean, with Greenland as the only major landmass. In 1995 the total generation of electrical energy generated in Greenland was 288 GWh [*Statistics Greenland*, 1997], and because of the low population density, there is no transmission network between the towns. This is less than 1% of the electrical energy generated by Newfoundland and Labrador Hydro in the same year [*Hydro*, 1997]. As the PLHR source has such an extreme geographical distribution, it seems reasonable to expect this to influence the spatial distribution of MLR if PLHR produced MLR (or was even indirectly linked to the generation of MLR). Thus we would expect to see a pronounced east-west asymmetry in the distribution of arrival directions of MLR observed at Halley. We have undertaken a study of the arrival directions of MLR events using the Halley VLF/ELF Logger Experiment (VELOX) multichannel receiver [*Smith*, 1995]. This is the first-time this technique has been applied to MLR. Because of the use of two vertical loop antennae, there is a 180° ambiguity in the azimuth direction measured by the VELOX receiver. However, this ambiguity will not be significant in our study; MLR events are known to be plasmaspheric [*Koons*, 1985], so we then only include MLR events with UT times between 0500 and 1800 UT where the plasmapause is known to be close to Halley during magnetically quiet periods ($Kp \leq 2$) [*Jenkins*, 1988]. The azimuth of 66 clear MLR events was measured using the VELOX data. These events were spread out over the 4-month data set in much the same way as the MLR occurrence rate varies by month [*Rodger et al.*, 2000, Figure 4]. We then

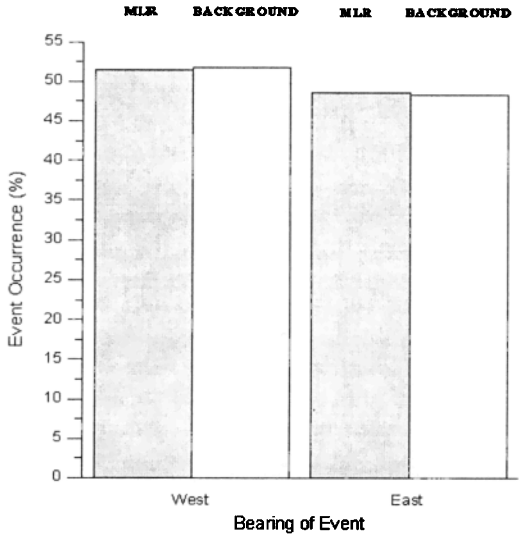

Figure 3. Comparison of the relative bearing of MLR activity observed at Halley (dark grey) and the background wave activity (light grey).

applied two additional restrictions upon the data set: (1) bearings within ±5° of the north-south meridian were removed to exclude the possibility that small measurement uncertainties could lead to the incorrect designation of an event as westerly or easterly, and (2) a 40° sector was removed around the east-west line to take into account that the L shells at Halley are angled relative to the east-west direction (thus a 20° exclusion was applied symmetrically to both easterly and westerly events to avoid bias). The ratio of the 35 MLR arrival directions remaining is shown as the dark grey bars in Figure 3. Figure 3 shows a slight east-west asymmetry which could be taken as evidence for a link to PLHR. However, if we assume that the MLR bearings have Poissonian statistics, the difference between the arrival directions is much less than one standard deviation and as such is statistically insignificant.

An underlying asymmetry in the bearing of activity at Halley should be caused by the South Atlantic Anomaly (SAA) [*Ladwig and Hughes*, 1989; *Smith et al.*, 1991]. As an additional check, we therefore compare the east-west ratio seen in the MLR data with that of the background activity observed at Halley. If the background activity varies in a similar way to the MLR, we would conclude that the MLR events are not being generated by power lines located to the west of Halley's conjugate region.

The presence of background activity and the frequency of this activity were determined using the MLRSCAN data, examining the first minute of every fifth hour of the four months in question for continuous wave activity (e.g., hiss and chorus) anywhere in the frequency range 1.5-5 kHz. This produced 591 samples over the 4-month period with a uniform distribution in LT. An extended survey was included for December, as the sample set was otherwise only 24 events. The first week of December was examined for activity at each hour (thus preserving the uniform distribution in LT), bringing the total number of minutes containing activity in December to 45. The azimuth of the background activity was determined from the VELOX data, and any event with high azimuthal scatter was rejected. A total of 212 events were identified in the survey, which dropped to 87 events once the restrictions previously applied to the MLR events were applied here.

The result of this survey of background events is shown as the light grey bars in Figure 3. As is clear from Figure 3, the difference between the MLR events and the background wave activity is small; in fact, the relative occurrence rate is the same for both MLR and background within the quantization error of the two sets of events. Figure 3 clearly shows (once again) that there is no bias in bearing toward regions that generate PLHR, and thus there appears to be no evidence for a relation to PLHR.

3.4. Association With Geomagnetic Activity

MLR is only weakly linked to geomagnetic activity. There is no association between MLR occurrence and immediate geomagnetic disturbances, but there is a small tendency for MLR to occur after 24-48 hours after very large storms ($Kp > 6$) [*Rodger et al.*, 2000]. However, it is known that geomagnetic activity gives rise to electric potential differences between different points on the Earth's surface which can cause extraneous quasi-DC currents to enter electric power transmission systems through their grounding points [e.g., *Boerner et al.*, 1983]. These geomagnetically induced currents (GICs) can cause saturation in electrical transformers, leading to distortion of the electrical waveform and hence the injection of additional harmonics into the electrical transmission network [*Kappenman and Albertson*, 1990]. Balloon-based measurements during magnetic storms have observed enhancements of PLHR [*Tomizawa and Yoshino*, 1984], which would be expected to radiate into the magnetosphere with no delay. Statistics of GICs observed in the Finnish power system indicate that GIC events with 30-40 A current occur ~700 times per year [*Viljanen and Pirjola*, 1989] and that in geomagnetically active times, "large GICs" (>50 A) can occur >200-300 times a year [*Viljanen and Pirjola*, 1994]. The fact that MLR shows only a delayed association with geomagnetic activity is further evidence for the lack of a link between MLR and PLHR.

3.5. The Sunday Effect in MLR Occurrence

It has been argued that the hebdomadal (7-day) cycle is a uniquely human cycle which is unlikely to be simulated by natural activity. As there is a lower usage of electrical power during the weekends (especially Sundays) owing to the decrease in industrial activity, any phenomena associated with PLHR might be expected to show a hebdomadal periodicity. For example, measurements of the power of geomagnetic variation in the ULF band in central Italy showed contamination linked to the hebdomadal cycle, with effects linked to "daylight saving" time changes as well [*Villante and Vellante*, 1998]. It has been reported that MLR observed at Siple and Eights showed a strong dependence upon the day of the week; MLR occurrence on Sunday was found to be only ~15% of the maximum weekday occurrence rate [*Park and Miller*, 1979]. The corresponding difference in the peak load of Hyro Québec was only ~15%. The strong association between MLR occurrence by day of week and the corresponding electrical load in the industrialized conjugate hemisphere appeared to be strong evidence for linking the MLR with PLHR.

The occurrence rate of MLR events observed at Halley by day of week is shown in Figure 4a. For operational reasons there were small differences in the number of minute-long recordings for some days of the week (no more than 10% of the mean). The occurrence rate shown in Figure 4a represents the

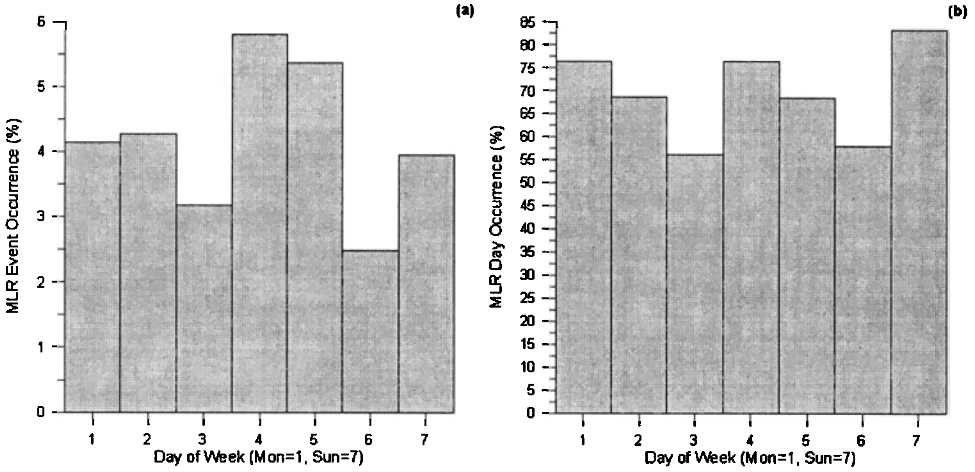

Figure 4. The variation in MLR activity at Halley by UT day of week, showing (a) the occurrence rate of MLR events and (b) the occurrence rate by MLR day, as examined by *Park and Miller* [1979] (see text for definition).

number of MLR events observed on a given day of the week throughout the 4 months of data (which total 477), divided by the number of minute-long recordings which were examined on a given day of the week (which total 11,448). In this case the day of the week is taken for UT, and as is clear, Figure 4a shows no evidence for a Sunday effect. The average occurrence rate of MLR on a given day in this data set is ~4.2%, with a variability of 1.5%. This variability is not large enough to mask the Sunday effect reported by *Park and Miller* [1979], which would be equivalent to a Sunday MLR occurrence rate of 0.7% in our data. Park and Miller reported that the Sunday effect was present in observations made in 1974 and 1975, using roughly the same number of weekend and weekday observations included in our analysis. The Monday-Saturday MLR occurrence rate of Park and Miller shows similar variability during the week as that seen in our data set for the entire week (Monday-Sunday). One can also look at their data taking the day of week for LT conditions at Newfoundland and the east coast of the USA. In neither case is there a significant Sunday or weekend effect (not shown).

In the case of Figure 4a we used the definition of an MLR event described in section 2. In the original presentation of the Sunday effect, *Park and Miller* [1979] took an event as a "PLR day" which was counted if MLR activity was observed sometime during the day regardless of what fraction of that day's data were sampled. In the 255 days which were surveyed, 44 days met the criteria to be included as a PLR day. If we adopt an MLR day as a day which includes at least one MLR event, we can examine our data set in exactly the same way as they examined theirs (note, of course, that we assume that an MLR day is counted once, no matter how many MLR-containing minutes that day might contain). In the 4-months data included in our survey of Halley data, there are 122 days, 85 of which are MLR days. The MLR day occurrence is shown in Figure 4b. As is clear, there is no Sunday or weekend effect present in this curve.

One possibility which might explain the differences between the results from 1973 to 1975, when *Park and Miller* [1979] did their study, and our 1995 data is that the relative difference between electrical load on weekdays and weekends could be smaller now than it was ~20 years ago. As noted above, there was a ~15% difference between Sundays and the peak load on a weekday. This difference was similar in France in 1983 [*Molchanov et al.*, 1991]. In order to examine this we have made use of electrical data from the state of Texas from May to October 1998 (data provided by M. Zehani, Dataphase, 1999). The difference between weekdays and weekends is indeed smaller, the average maximum peak electrical consumption on Sundays in Texas being ~9% smaller than the weekday maximum. However, Park and Miller reported that a ~15% difference in electrical consumption could bring about an 85% change in MLR occurrence. Thus it seems likely that a ~9% difference in electrical consumption should bring about an observable change in MLR occurrence in our data (although it is not clear that seasonal or regional differences might not be more significant than changes over the last ~24 years). It has been proposed that the large sensitivity of MLR occurrence to electrical load changes might be due more to differences in the load pattern rather than to actual consumption [*Molchanov et al.*, 1991]. It is possible that such changes might not have taken place in the industrialized conjugate region in 1995,and hence masked any Sunday effect. While this cannot be ruled out, we conclude that the lack of a hebdomadal cycle in our MLR data provides additional evidence that MLR is not caused by PLHR.

3.6. The Sunday Effect in Halley Wave Intensity

In addition to presenting the "Sunday effect" in MLR occurrence, *Park and Miller* [1979] searched for a weekend effect in magnetospheric wave intensity in the 2- to 4-kHz frequency range. The analysis of 2 years (1974-1975) of Siple station VLF data showed a distinct intensity minimum on Sunday in comparison with the rest of the week. This is shown in Figure 5, which is taken from the work of Park and Miller. If PLHR did have a significant influence on the overall wave activity at Halley, it would likely affect the arrival directions of the background wave activity, thereby invalidating the results of section 3.3. In order to check for this effect we made use of the 1-s-averaged data from the average (scalar) and minimum intensity channels from the Halley VELOX receiver to produce hourly averages for ~4 months (days 108-226) of 1995. Figure 6 shows the daily variation of the wave intensity in the minimum channel for weekends (Saturday-Sunday) and weekdays (Monday-Friday). The minimum channel is shown as this should lessen the effects of impulsive signals such as sferics and whistlers, although it is clear that the upper frequency bands (6 and 9.3 kHz) are dominated by the diurnal

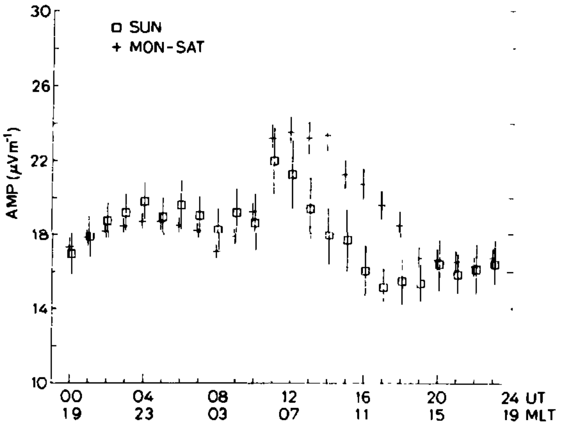

Figure 5. Daily variation of 2- to 4-kHz wave amplitude at Siple, Antarctica, showing differences between Sunday and Monday-Saturday. The vertical bars indicate standard deviation from the mean [from *Park and Miller*, 1979].

variation of lightning [*Clilverd et al.*, 1999]. The vertical bars on the weekday curve indicate one standard deviation from the mean amplitude level. Only two frequency channels show any times where the difference between weekends and weekdays is more than 1 standard deviation. These occur in the 3- and 4.25-kHz channels, where the few points lying outside one standard deviation have larger amplitudes during the weekend rather than smaller. This is opposite to that expected if there was a link to reduced weekend power consumption, and is also not statistically significant, as there are only five occasions where the difference is more than 1 standard deviation from the mean. There is also no difference between weekend and weekday wave intensities seen in the average amplitude channel (not shown), which is essentially the same as Figure 6. There is also no Sunday effect apparent in our data, examined by averaging the intensity data for Monday-Saturday and comparing it with Sundays.

3.7. The "Holiday Effect" in Halley Wave Intensity

Heavy industry (assumed to be the significant source of harmonics and hence PLHR) may be more likely to alter their operations for major North American public holidays. The conjugate of Halley is located in Canada, and hence Victoria Day (third Monday in May), Canada Day (July 1), Labor Day (first Monday in September), Thanksgiving Day (second Monday in October), and Christmas (December 25) may be used as tests of possible PLHR influence on geospace. The generating facilities in eastern Canada export significant quantities of power to the United Staes, and hence American holidays such as Independence Day (July 4) and Thanksgiving Day (last Thursday in November) may also be relevant. Electrical consumption figures from Texas indicate that the decrease associated with July 4, 1998, was ~25%, while that for Thanksgiving (November 26, 1998) was ~17%. These changes are somewhat larger than those mentioned previously for Sunday's power consumption and therefore should be considered for potential effects in the Halley data. To investigate this we analyzed 4 years (1994-1997) of 3-kHz VELOX data using a superposed epoch technique centered on each holiday mentioned above. The results are shown in Figure 7. United States' Independence Day appears at day 3 in the Canada Day panel. Christmas Day is not shown, because of data gaps during that period due to system maintenance during the Antarctic summer. The plots show 24-hour median intensities, although 1-, 2-, 3-, 4-, 6-, 8- and 12-hour plots were produced but are not shown here. No consistent change in 3-kHz intensity can be observed during any of the major North American holiday periods. Hence we conclude that there is no evidence of a holiday effect in the Halley data.

4. Discussion

We have shown that there is no clear link to PLHR in any of the tests we have applied to our Halley observations. Three of the examinations reported above have not been considered before in relation to PLHR, but there are previous studies concerning the spacing of MLR and the Sunday effect which deserve further discussion here.

4.1. Spacing of MLR

It is generally reported [e.g., *Bullough*, 1995] that the first paper on MLR [*Helliwell et al.*, 1975] showed that the lines tend to have spacing clustered ~120 Hz, which was explained through the tendency of the Canadian power system to radiate at odd harmonics of the fundamental transmission frequency (60 Hz). However, a reexamination of this paper does not clearly support such a strong statement. The evidence for this conclusion seems to be based on the analysis of 45 min of data from Siple Station, where the MLR lines had spacings mostly between 90 and 140 Hz, with a peak at 129 Hz [*Helliwell et al.*, 1975, Figure 3]. However, the same study also reported on the examination of 14 min of Eights data which showed no tendency for near 60-Hz harmonics and an example from Suffield, Alberta, which showed only a slight tendency for separations which were multiples of 50 Hz (within 10 Hz). Previous reports on the spacing of MLR are discussed by *Rodger et al.* [1999].

There is, in fact, little evidence in the literature that MLR lines should have spacings near to 50 and 60 Hz. This has been recognized by some authors [e.g., *Bell et al.*, 1982; *Parrot*, 1994] but is not seen as contradictory with a PLHR source for MLR. However, as is shown in this paper, there is little evidence in the Halley data for any link between PLHR and MLR.

4.2. Sunday and Weekend Effects

Halley data have previously been examined for a Sunday or weekend effect. An examination of the minimum intensity 1-kHz frequency band centered on 3.2 kHz over January-November 1972 showed a strong minimum on Sundays [*Yearby et al.*, 1981]. *Yearby et al.* [1981] urged caution in linking their result with PLHR, noting that their data may have been influenced by instrumental effects. A more extensive analysis of Halley data using the 3.2-kHz average intensity channel was undertaken using 1984 data. No significant difference was found between the daily variation for weekdays and that for Sundays [*Jenkins*, 1988]. Observations made at Syowa Station, Antarctica (69°00'S, 39°35'E), also showed no evidence of a Sunday effect in 0.75-, 1.2-, and 2.0-kHz channels over the period July 1981 to December 1983 [*Higuchi et al.*, 1986].

It is thus clear that the Sunday effect is not present in the Halley data, and thus that PLHR is not a significant factor in observations made there. It should be noted that the Sunday effect is not necessarily accepted as real. No significant Sunday

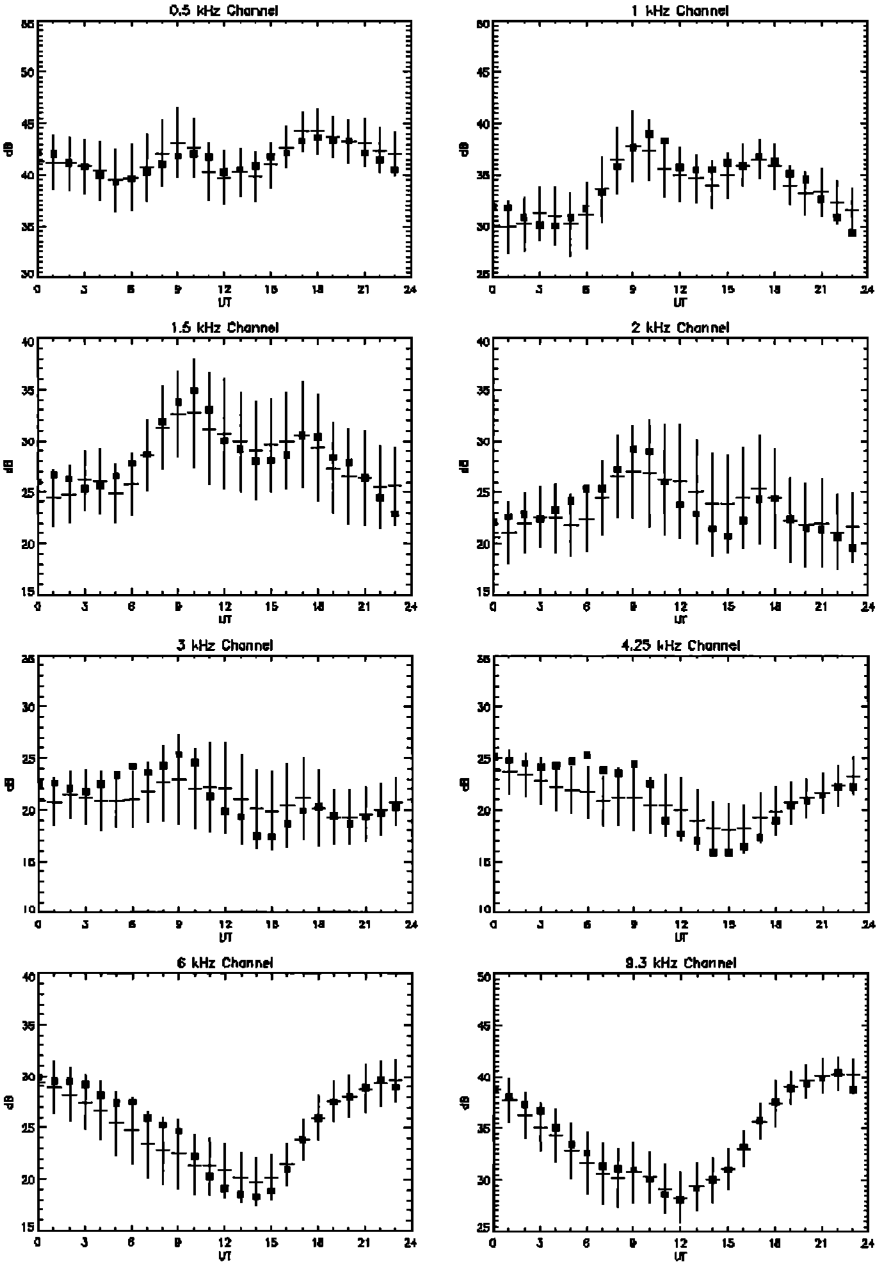

Figure 6. The variation in received wave amplitudes in decibels in the instrument's eight frequency channels, showing the differences between weekdays (crosses) and weekends (squares). The vertical lines indicate ±1 standard deviation from the mean.

effect was found in OGO-5 satellite data [*Thorne and Tsurutani*, 1981], although a more recent study reported that the average electric field amplitude at 72 Hz was 93% higher on Mondays than on Saturdays [*Parrot et al.*, 1991]. This very large effect has been attributed to differences in the power system current distribution in the weekend as compared to weekdays [*Molchanov et al.*, 1991], rather than to differences in the power consumption, which is ~15%. A different attempt to explain the Sunday effect observed by *Park and Miller* [1979] is the idea that 7-day ionospheric variations can arise from the phase-locking of the day of a week with the almost 4-week rotation of coronal holes (a concept put forward by T. J. Rosenberg and discussed by *Dowden and Fraser* [1984]).

It appears that PLHR was not a significant factor in the Halley VLF data in 1984 or in 1995. Over the time period 1984-1995, electricity sales in the United States grew by ~36% [*Hutzler*, 1999]. PLHR was also found to be not significant at Syowa Station using data from 1981-1983. It is not clear that the growth in harmonic content (and hence PLHR) will have grown linearly with electricity sales. In fact, there appears to be an increase in the use of diode rectifiers and silicon-controlled rectifying switching devices, which are two of the greatest causes of harmonic distortion in current electrical supply networks [*Stebbins*, 1996]. Distortion can also be created by a number of systems including the switching power supplies of computers and electronic controllers. By the year 2000 it is estimated that upward of 60% of all electricity used in the United States will first pass through an inherently nonlinear semi-conducting device, compared with ~40% in 1996 [*Stebbins*, 1996]. It is not clear, however, that this is grounds

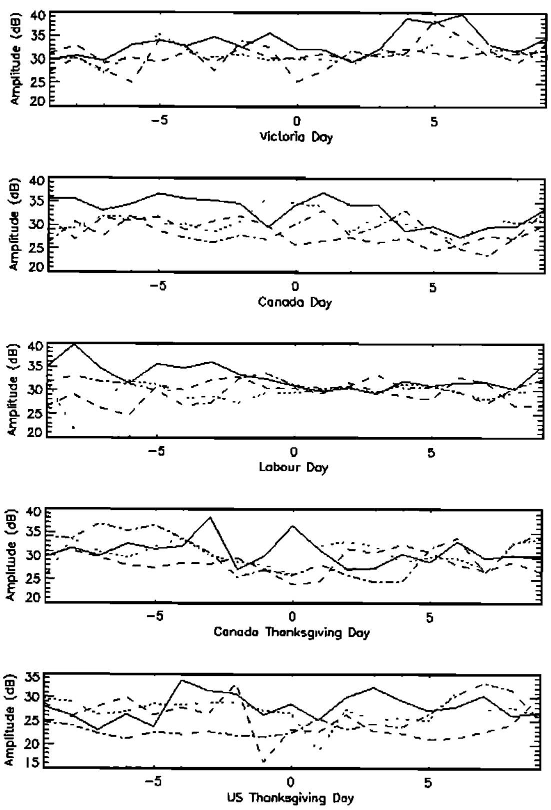

Figure 7. The variation in received wave 24-hour median intensities in decibels of the 3-kHz channel using a superposed epoch technique for 1994-1997 data, centered on major North American holiday periods. The 1994 data is shown by a solid line, 1995 data is shown by a dashed line, 1996 data is shown by a dotted line, and 1997 data is shown by a dash-dot line.

for concern in terms of man-made "pollution" of the magnetosphere.

Our study suggests that there was no effect by the North American power transmission system on the parts of geospace visible from Halley. While the size or quality of the electrical transmission system might pass a threshold beyond which an effect may be visible in future, previous work suggests that this is a long way off. The Siple VLF transmitter has been used to simulate PLHR effects in the magnetosphere, transmitting a radiated power of ~0.5 W [*Park and Chang*, 1978]. In contrast, estimates of the radiated power from several power lines in the Halley conjugate region were found to be less than 1 μW per harmonic [*Yearby et al.*, 1983]. Thus, at that time, PLHR sources appeared to be too weak by a factor of ~10^5 to cause directly observable effects. It remains unclear whether weaker PLHR sources could have an indirect effect on overall wave activity observed at Halley. This question might be answered by modeling studies.

5. Conclusions

Observations of MLR activity in data collected from Halley, Antarctica, during June, July, September, and December 1995 lead us to the following conclusions:

1. The diurnal variation of MLR occurrence at Halley does not resemble the expected load pattern in the industrialized conjugate hemisphere.
2. The west/east ratio of MLR is the same as all other "background" activity at Halley (within quantization error). PLHR in the conjugate hemisphere is expected to be highly asymmetric.
3. MLR does not show an immediate association with geomagnetic activity but rather shows a weak increase in MLR activity 24-48 hours after magnetic disturbances [*Rodger et al.*, 2000]. Immediate enhancements in PLHR have been observed by balloon associated with magnetic storms.
4. There is no evidence of a Sunday, weekend, or other 7-day cycle in the occurrence of MLR. Such an effect might be expected if MLR occurrence was linked to electrical consumption in the industrialized conjugate hemisphere, as this is ~10-15% lower on Sundays than during the weekday peak.

Taken together these results strongly point to MLR as a natural VLF emission, not primarily caused by PLHR. In addition, Halley data have been examined to determine whether VLF emissions (and not just line radiation) are influenced by PLHR. This study has lead to the following:

1. None of the eight channels of the VELOX receiver (0.5-9.3 kHz) showed a significant difference between weekdays and weekends (or Monday-Saturday and Sunday) in either the minimum or scalar amplitude channels.
2. No consistent change in 3-kHz intensity can be observed during any of the major North American holiday periods. Hence we conclude that there is no evidence of a holiday effect in the Halley data.

It appears that PLHR is not a significant influence on geospace as viewed from Halley.

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