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Investigating seismoionospheric effects on a long subionospheric path

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Abstract. We examine the possibility of earthquake precursors influencing the subionospheric propagation of VLF transmissions. We consider the long (12 Mm) path from northeastern United States to Faraday, Antarctica (65°S, 64°W), during 1990-1995 and investigate the subionospheric amplitude variation of signals from the NAA communication transmitter (24.0 kHz, 1 MW) in Cutler, Maine, with particular emphasis on possible changes induced by seismic events occurring in South America. We have analyzed the changes in timing of modal minima generated by the passage of the sunrise terminator over the Andes, i.e., the "VLF terminator time"(TT) method. The anomalous variations in timing throughout the year are of a size and occurrence frequency similar to those previously reported, i.e., ±0.5–1 hour and 1–2 per month. However, we find that in these anomalous cases, the time of the sunrise modal minimum does not change significantly, but rather, the minimum becomes insufficiently deep to be detected, and the time of the next nearest minimum is logged. Our analysis indicates that the occurrence rate of successful earthquake predictions using the TT method cannot be distinguished from that of chance. Additionally, the level of false earthquake prediction using the TT method is high.

1. Introduction

Radio waves from VLF transmitters propagate inside the waveguide formed by the lower ionosphere and the Earth's surface. Significant variations in the received amplitude and phase arise from changes in the lower ionosphere. These variations include those driven by changes in solar zenith angle [*Thomson*, 1993], solar flares [*Mitra*, 1974], lightning-induced electron precipitation [*Helliwell et al.*, 1973], and red sprites [*Hardman et al.*, 1998]. Phase and amplitude perturbations associated with earthquakes have also been reported. A study of the signals received from Omega navigation transmitters (10.2-13.6 kHz) during 1983-1986 found that 250 out of 350 earthquakes with magnitude (M) greater than 4 were associated with phase and/or amplitude variations [*Gokhberg et al.*, 1989]. These perturbations lasted between 1.5 and 7 hours and occurred 1–5 days before the shock, where the earthquake epicenter could be up to 700 km from the transmitter receiver great circle path (GCP), and mostly (90%) occurred during nighttime propagation. Gokhberg et al. suggested that "anomalous areas" in the lower ionosphere could be changing the radio propagation conditions before earthquakes. Very similar observations have been made by *Gufeld et al.* [1994], who discussed the possibility of direct prediction of seismic activity 20–30 days before the shock, and by *Hayakawa and Sato* [1994], who examined six $M > 5.5$ earthquakes lying within the first Fresnel zone of the GCP. In the latter case, however, the propagation anomalies (amplitude >2 times the standard deviation, σ) could be of much shorter duration, from 10 min to "several hours," and occurred up to 2 weeks before and after the shock. The statistical basis of the studies which make use of anomalies in Omega transmissions has been examined by *Michael* [1996], who concluded that the reported anomalies are probably not earthquake precursors but were due to random, rather than physical, processes.

Signals from powerful communication transmitters have also been examined for perturbations associated with earthquakes. *Morgounov et al.* [1994] used the U.S. Navy transmitter NWC (21.8°S, 114.2°E, then at 22.3 kHz) in addition to the Omega navigation transmitters, both recorded at Inubo, Japan. Amplitude recordings were selected around the occurrence of five $M \geq 7.0$ shocks, located "relatively near the great circle propagation paths" [*Morgounov et al.*, 1994]. The

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authors report that one extremely large earthquake (28.1°S, 176.4°W, $M = 8.3$) was associated with perturbations observed 1-2 days before the shock seen on transmissions from Omega Hawaii (21.4°N, 157.8°W), about 6000 km away from the epicenter. Variations in received amplitude associated with seismic activity have also been reported on 216-kHz transmissions in southern Europe [*Bella et al.*, 1998].

A new approach to examining subionospheric signals for seismic effects was presented by *Hayakawa et al.* [1996] and applied to the Hyogo-ken Nanbu earthquake (January 17, 1995, $M = 7.2$, commonly known as "Kobe" after the nearby Japanese city). These authors used recordings of signals from the Omega Japan transmitter (34.6°N, 129.5°E) observed at Inubo (35.7°N, 140.9°E), about 1000 km away. The earthquake focus was located ~70 km from the GCP. Since the studies outlined above had generally dealt with long distance propagation (large distances between the transmitter and receiver), *Hayakawa et al.* [1996] considered the deviations of the terminator times, which they suggest is more appropriate for short propagation paths. The authors defined the terminator times (TT) as the times when a minimum occurs in the received phase (or amplitude) near the times of sunrise and sunset. A few days before the earthquake the evening terminator time was found to deviate significantly from the monthly averaged evening terminator time, exceeding the 2σ level. At peak, the observed evening terminator time was nearly 50 min later than the monthly average value. The dusk terminator time effect was clearer than that for the dawn. Simple theory was presented which suggested that the observed effect can be explained by decreasing the VLF reflection height by ~0.7 km. The same data are presented for the same earthquake in the almost identical study by *Molchanov et al.* [1998], who used the same theory but suggested that a decrease in the VLF reflection height of ~2 km would explain the observed deviation. A detailed discussion of the modeling of terminator times is given by *Rodger et al.* [1999].

The terminator time method has been applied to 10 other large ($M \geq 6.0$) earthquakes [*Molchanov and Hayakawa*, 1998]. Five of these shocks were associated with evening terminator time deviations, were reasonably shallow (0-80 km), and occurred within 70 km of the GCP from Omega Japan to Inubo. The deviations ranged from ~15 to ~32 min. It is unclear whether more distant earthquakes might be associated with a terminator time effect, as the other five presented in the study were also deep (>80 km), which was believed to mask the influence on propagation.

All of the studies using the terminator time method have involved the short path from Omega Japan to Inubo. All Omega stations ceased transmission at 0300 UT, September 30, 1997, after up to 26 years of operation. Thus the application of the terminator time method to much longer paths and communication (rather than navigation) transmitters needs to be examined. In this paper, we consider the 12-Mm path from northeastern United States to Faraday, Antarctica (65°S, 64°W), during 1990-1995. We investigate the subionospheric amplitude variation of signals from the NAA communication transmitter (24.0 kHz, 1 MW) in Cutler, Maine, with particular emphasis on changes possibly induced by seismic events occurring in South America.

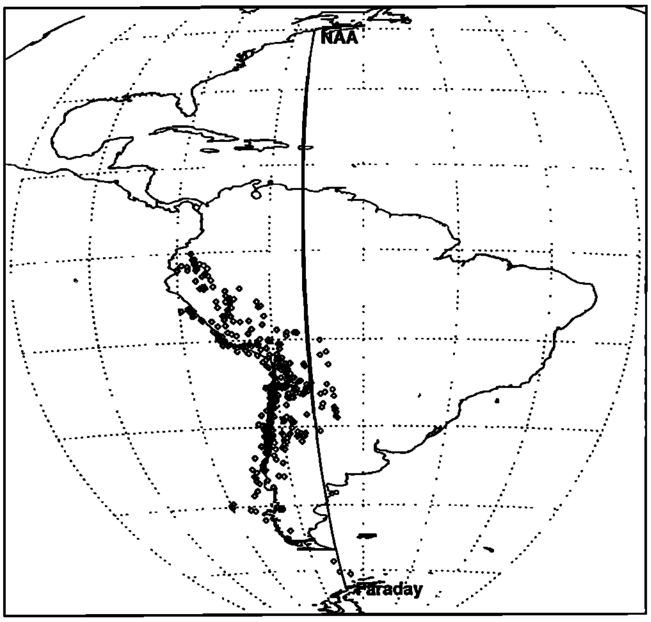

Figure 1. A map of the great circle path from the NAA transmitter to Faraday, Antarctica. The path passes through the seismically active region of the Andes. The locations of earthquakes with magnitudes ≥5.0 that occurred between 1990 and 1995 between 60°W-80°W and 0°S-65°S are indicated on the map.

2. Results

The GCP from NAA to Faraday passes close to the seismically active region of the Andes, South America. Figure 1 shows a map of the path relative to the landmasses of America and the Antarctic Peninsula. The locations of earthquakes with magnitudes ≥5.0 that occurred between 1990 and 1995 between 60°W-80°W and 0°S-65°S are indicated on the map provided by the Northern California Earthquake Data Center (NCEDC). The lower limit of M=5.0 has been chosen for this study to provide good comparison with previous work. In the course of a year, about 10 earthquakes with magnitudes ≥5.0 occur close to the NAA Faraday GCP, i.e., 200 km, within the first Fresnel zone used by *Molchanov and Hayakawa* [1998], whereas the majority occur at greater distances.

To study the possible effects of seismic activity on the amplitude of signals from VLF communication transmitters, we use a 6-year data set from an Omega and minimum-shift keying (OMSK) instrument at Faraday, built by the University of Otago and described by *Dowden et al.* [1994]. The system records the amplitudes of the subionospheric signals from transmitters with a time resolution of 1.25 s, although for this paper we shall confine ourselves to analysis using 1-min average data. A typical selection of data from the experiment is shown in Figure 2. The amplitude is plotted against UT for 20 sequential days in January 1994. There is a data gap between 1430 and 1630 UT each day caused by data archival. The high scatter of points with low values around 1700–2000 UT represents noise levels dominated by sferics when the transmitter was occasionally off-air. The bulk of the variations observed are due to propagation conditions rather than to transmitter or receiver effects. During the daytime the lower ionospheric boundary at about 70 km is generated by photoionization from solar radiation. The boundary is well defined, and its characteristics vary smoothly with changes in solar zenith angle throughout the day. Thus the resultant signal amplitude is repeatable from day to day. At night the lower ionospheric boundary at about 85 km lacks definition, and thus the propagation conditions vary significantly along the path. This results in rather variable amplitudes with relatively poor repeatability from night to night.

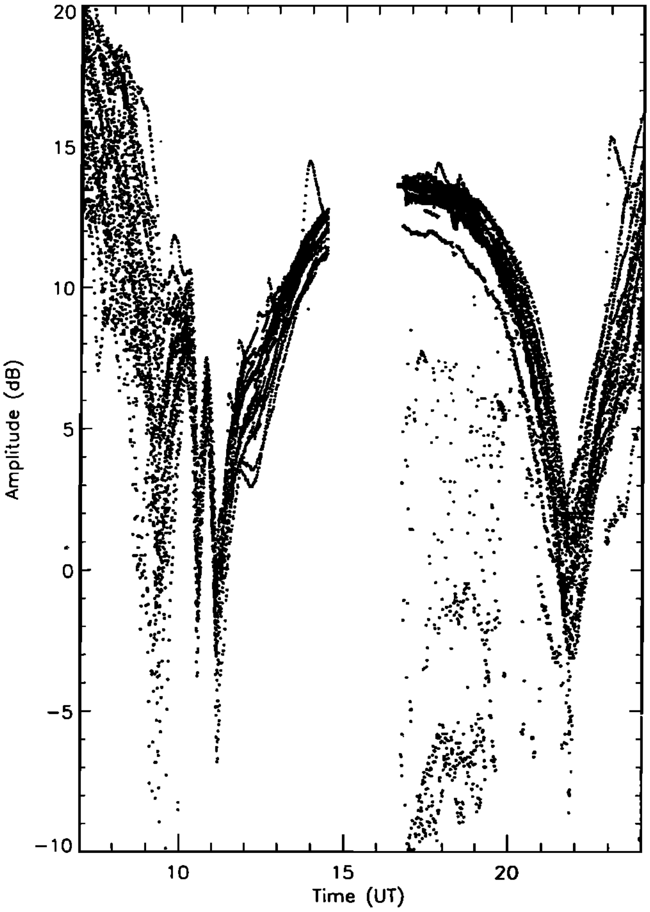

Figure 2. The amplitude variation of NAA plotted against UT for January 1–20, 1994.

During the transition between nighttime and daytime propagation conditions, several short-lived, but deep, minima in amplitude are seen in Figure 2, each lasting only about 10-20 min. The generation mechanism for sunrise modal minima is generally accepted to involve significant mode conversion where the sunrise terminator crosses the propagation path (modeled by *Crombie* [1964] and validated by *Walker* [1965]). For the case where the transmitter is in darkness and the receiver is in daylight, the magnitude of the sum of the interfering modes at all altitudes at the location of the terminator determines whether receivers, on the same great circle path, anywhere on the dayside of the terminator, and more than 1000 km from it, are simultaneously experiencing maxima or minima. If the transmitter is in daylight while the receiver is in darkness, then typically the dominant day mode at the terminator will be converted into a range of nighttime modes. These will interfere with each other, thus producing a spatial succession of maxima and minima at receivers located along the GCP on the nightside of the path. The succession of maxima and minima move with the terminator, and at a fixed location, a receiver would observe a series of modal features as they passed overhead. A detailed discussion of the generation of modal minima on the NAA-Faraday path is given by *Clilverd et al.* [1999].

It has been suggested that short-term deviations in the normal seasonal variation of sunrise modal minima times are a result of the influence of effects from seismic activity, the study of which has become known as the terminator time method [*Hayakawa et al.*, 1996]. The seasonal variation in the time of occurrence of a minimum in signal strength received at Faraday from NAA follows the variations in local sunrise times at well-defined locations on the GCP possibly linked to modal minima in the upper portion of the Earth-ionosphere waveguide [*Clilverd et al.*, 1999]. This seasonal time variation can easily be removed from the data, allowing the influence of other effects to be studied. An example of this is shown in Figure 3. The seasonal sunrise time variation removed was for a location slightly south of the seismically active region in the Andes (i.e., 30.0°S, 65.8°W). The resultant minimum can be seen occurring at about 0900 UT in Figure 2. In Figure 3, the x axis represents the day of the year in 1994. The right-hand y axis represents the variation (in hours) of the time of occurrence of the nearest minimum feature in the OMSK data with respect to local sunrise at the location of the terminator and at an altitude of 75 km. Typically, there is only up to a 0.15 hour (9 min) difference between the predicted and actual minimum occurrence time. However, on some anomalous occasions this difference is up to 0.7 hour. Figure 3 indicates that there are 17 timing changes in 1994 which are greater than 2σ (defined as a TT event) calculated over the whole year and shown as horizontal dashed lines. Clusters of $>2\sigma$ events within 5 days are counted as a single event as in previous work. This rate of occurrence is similar

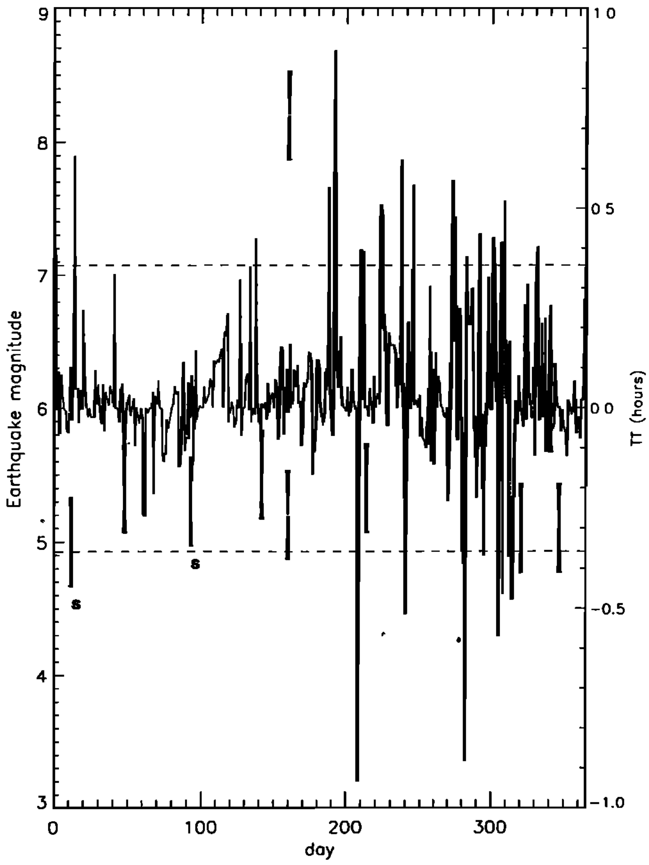

Figure 3. The variation in the timing of minima in 1994. The occurrence and magnitude of seismic activity in the Andes are indicated by the hourglass symbols. The timing changes equivalent to 2σ deviations are indicated by the horizontal dashed lines. Earthquakes within 50 km of the surface are denoted by letter S. See text for more details.

to TT event data shown in previous work [*Molchanov and Hayakawa*, 1998] and is consistent throughout the period studied. In the data presented in this study, the largest changes in minimum time are associated with the next terminator mode-conversion region. This is typically ~2000 km at large distances from the transmitter, and it takes the terminator about 0.5–1 hour to move this distance at solstice for the NAA-Faraday path [*Clilverd et al.*, 1999]. In effect, the time of the minimum does not change significantly, but rather, the minimum becomes insufficiently deep to be detected, and the time of the next nearest minimum is logged.

Superposed on Figure 3 are hourglass symbols which indicate the day of occurrence and magnitude of seismic activity close to the NAA-Faraday GCP (within 200 km) during 1994. The activity magnitude is represented on the left-hand y axis and relates to the center of the hourglass symbol. In addition to questions about the magnitude of seismic events that potentially influence the subionspheric propagation of VLF signals, there has also been discussion about what depth of seismic event should be considered. Recently, earthquakes closer to the surface than 30-50 km have been suggested as most likely to affect the VLF waves [*Molchanov and Hayakawa*, 1998]. In Figure 3, seismic activity occurring at depths within 40 km of the surface is denoted by letter S, for "surface." In 1994, there does not appear to be a strong association between TT changes greater than 2σ and earthquakes, although a few earthquakes do occur within 10 days of TT events. This is discussed in more detail in the next section. The precise dates, times, distance from the GCP, and depth of the earthquakes are given in Table 1. The table additionally indicates whether a significant terminator time signature is detectable prior to (i.e., within 10 days before) or coincident with (i.e., within 24 hours after) the seismic activity. A multipanel plot of terminator time differences for all of the years in this study (i.e., 1990–1995) is shown in Figure 4. The format is identical to Figure 3. Periods where no data were collected are indicated by no lines being plotted, i.e., January–April 1990 and April–December 1991.

The 2σ criterion used in this paper, and in previous work, is often used as an approximation to the 95% confidence limit. This would be true of some distributions,

Table 1. Summary of Seismic Activity in the Andes in 1994

Date	Depth, km	Magnitude	Latitude, deg	Longitude, deg	Distance from Great Circle Path, km	TT Precursor	TT Coseismic
Jan. 12	10.0	5.0	-61.0	-62.7	100	no	no
Feb. 17	222.8	5.4	-23.2	-66.5	-58	no	no
April 3	37.9	5.3	-17.6	-64.8	131	no	no
May 22	192.2	5.5	-24.2	-66.8	-92	yes	no
June 9	631.3	8.2	-13.8	-67.5	-153	no	no
June 9	630.9	5.2	-13.8	-67.2	-122	no	no
Aug. 2	199.7	5.4	-24.0	-66.7	-86	yes	no
Nov. 17	273.7	5.1	-22.4	-66.0	-5	yes	no
Dec. 7	235.0	6.0	-23.4	-66.6	-70	no	no
Dec. 13	103.6	5.1	-24.1	-67.8	-193	no	no

TT, terminator time.

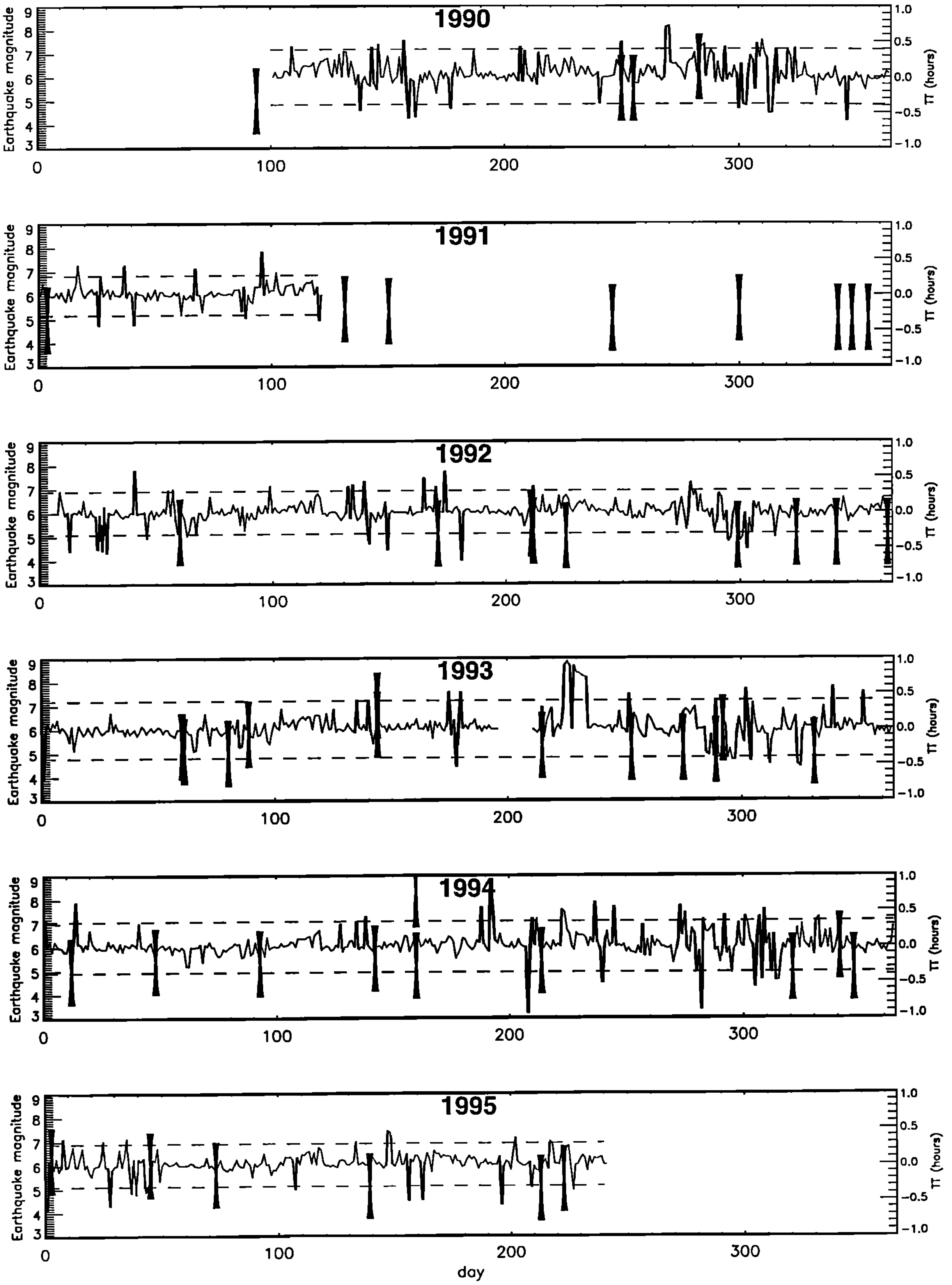

Figure 4. Same as for Figure 3, but for all data during 1990–1995.

including normal distributions, but not all. In Figure 5 we plot the normalized occurrence of all of the TT values in 0.05-hour bins against a time axis normalized by $(X\text{-}\mu)/\sigma$, where each independent measurement (X) is compared with the true mean (μ, which is 0.03 hour in this case) and divided by the standard deviation of the sample (σ, which is 0.2 hour here) [*Cooper*, 1969]. A normal distribution (solid line) is also plotted for comparison. The 2σ criterion is met at a value of 2 on the x axis. In the case of the TT events (shown as diamonds), 2σ does represent the 95% confidence limit (to within 0.5%), although there is no indication in the figure that the TT values have a normal distribution.

The influence of seismic activity on subionospheric VLF waves has been proposed via a mechanism causing the reduction in altitude of the lower ionospheric boundary, thus affecting the waveguide propagation conditions [*Molchanov and Hayakawa*, 1998]. An effect similar to this could be generated through the effect of increased magnetic activity. Enhanced particle precipitation, ionospheric heating, and traveling ionospheric disturbances could all be present during magnetic storms. In an attempt to study this effect we compared the terminator time differences shown in Figure 3 with the *Ap* index. The resultant plot of *Ap* and terminator time differences at 30.0°S, 65.8°W for 1994 is shown in Figure 6. *Ap* (denoted by dashed lines) is seen to increase occasionally above 30 nT in association with geomagnetic storms and typically remains high for 1 or 2 days.

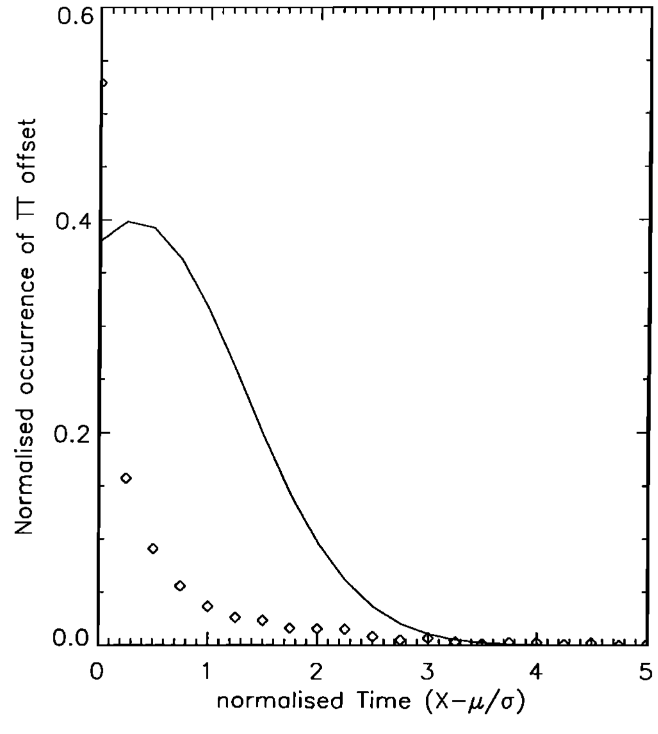

Figure 5. The distribution of terminator time (TT) values (diamonds) plotted against a normalized time axis. A normal distribution is plotted for comparison (solid line). See text for more details.

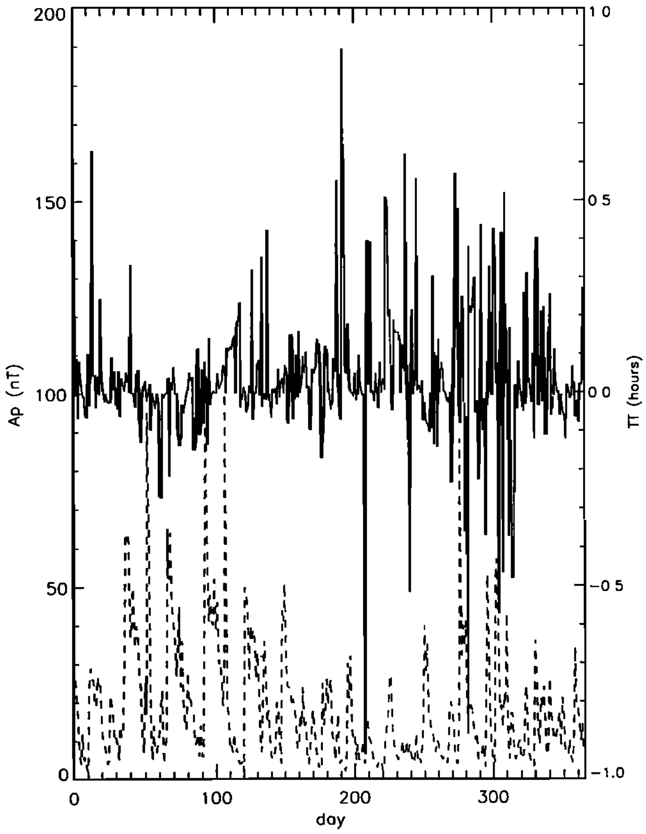

Figure 6. The variation in the timing of minima in 1994 compared with magnetic activity levels indicated by *Ap*.

Assuming levels of high geomagnetic activity to be represented by $Ap>30$ nT [*Clilverd et al.*, 1998], we looked for large TT changes within 2 days of the occurrence of $Ap>30$ nT. No association could be found between large changes in minima timing and the occurrence of high magnetic activity levels identified using *Ap*, other than those expected by chance; that is, in 1994 four out of 17 TT events (i.e., 1 in 4.2) occurred within 2 days of $Ap>30$ nT, and in 1993 there were four out of 19 (i.e., 1 in 4.8). Estimates of chance association gave between ~1 in 3 and 1 in 4 probability of coincidence.

3. Discussion

Using the National Oceans System Center (NOSC) long wave propagation capability code (LWPC) [*Ferguson and Snyder*, 1990], we model the nighttime propagation conditions along the path. The code computes modal conversion along the propagation path on a continual basis for typically 10 or more modes and is widely regarded as the most realistic model for VLF propagation problems. We use LWPC parameters for nighttime ionospheric conditions prescribed by NOSC which are typically sharpness (β) of 0.5 km^{-1} and effective height (h') of 84–87 km. The variation in NAA, 24.0-kHz, nighttime amplitude just below the lower ionospheric boundary (80 km altitude) with distance along the great circle path toward Faraday is shown in Figure 7 (long-dashed line). There is a gradual decrease in amplitude with distance, but there are also regions where the amplitude is significantly reduced due to interference between propagation modes. The waveforms depicted in Figure 7 can be thought of as a standing wave pattern as long as the nighttime ionospheric conditions remain unchanged. The effect of lowering a section of the lower ionospheric boundary is also shown. The dotted line represents the variation of nighttime amplitude from NAA at 80 km altitude as before; however, at about 5000 km from the transmitter the ionosphere has been lowered by 5 km for 1000 km of the path in order to model the possible effects of seismic activity on the ground below [*Rodger et al.*, 1999]. The lowering has the effect of reducing the dimensions of the waveguide and hence altering the location of modal minima "downstream" from the earthquake region. This should result in dayside minima occurring at different times from the nonperturbed case. The change in location observed with LWPC is ~200 km, equivalent to at most about a ±5-min change in minima timing, depending on season, and would therefore be undetectable in Figure 3 because of noise levels which are of similar order.

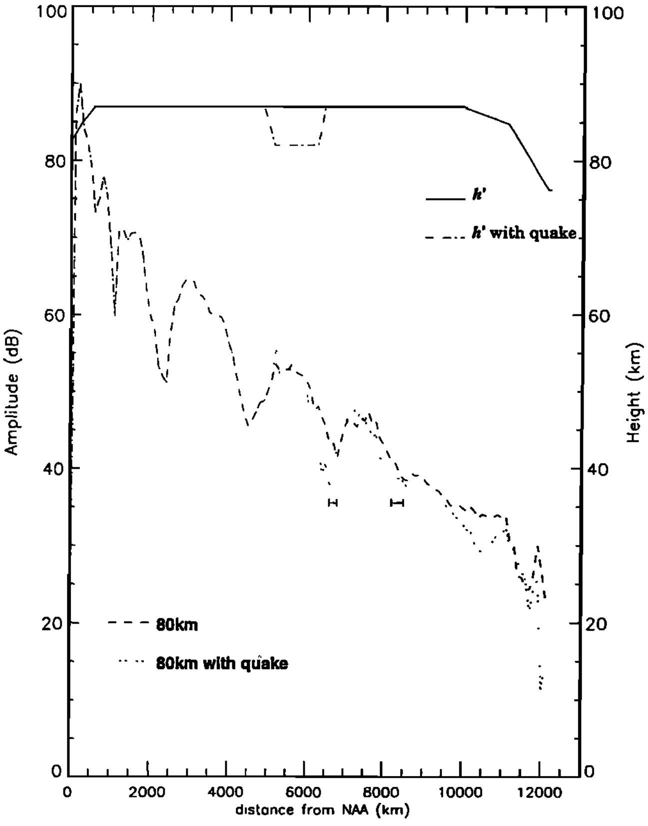

Figure 7. Long wave propagation capability code output at an altitude of 80 km, on the NAA-Faraday great circle path, shown by the long-dashed line with a 100-km resolution in distance. The effect of lowering a portion of the upper ionospheric boundary (h') by 5 km for a distance of 1000-km is shown by the dotted line. The movement of two modal minima is highlighted by horizontal bars with widths of 200–300 km. The lowering of h' from 85 to 80 km is represented by the dash-dotted line near the top of the plot.

Despite the modeling results, it may be possible that earthquakes are somehow influencing the timing of the minima by significantly more than 5 min. To distinguish a clear association between seismic activity and TT events or chance overlap, we consider the information in Table 1. The table allows an estimate of successful prediction of seismic activity using the TT changes greater than 2σ in 1994. This year is typical in that 17 TT events occurred with changes greater than 2σ. In line with previous work we took preseismic TT changes to be associated with earthquakes if a $\geq 2\sigma$ change occurred up to 10 days earlier. Coseismic TT events were considered positively associated if a $\geq 2\sigma$ change occurred only within 24 hours after an earthquake. Thus, given 17 TT events and a 10-day window, this would cover ~17×(10+1)=187 days of the year, although this is reduced slightly (35 days) by overlap between TT dates; that is, if two 10-day windows overlap by 3 days, we should predict earthquakes on potentially 17 days rather than 20. Thus any specific seismic event has a 152 in 365 (i.e., 1 in 2.4) chance of randomly falling within the criteria for successful prediction. Our table indicates that 3 in 8 (i.e., 1 in 2.7) predictions/coincidences were successful, very similar to chance. The number of seismic events in 1994 was reduced by two for our analysis because two events occurred on the same day and the January 12 event occurred on the daylight part of the path well south of the Andes, and as such the modal minimum whose timing is studied here would not be downstream. If we reduce the preseismic association criterion to 5 days, we would expect a 1 in 3.8 success rate by chance, allowing for overlap days. The actual success rate was 0 in 8 for the 5-day precursor window.

Analysis of all the years 1990-1995 is presented in Table 2. The rows represent a summary for each year. The number of seismic events were determined as described previously, i.e., $M>5.0$, within 200 km of the GCP, and located in the Andes. The number of successful "predictions" of earthquakes by the TT method using 10- and 5-day windows are indicated, as are the number of coseismic TT events. There are nearly 3 times as many TT events as there are earthquakes during the period of study. The success rate for predicting earthquakes using the 10-day window was 18 out of 35, i.e., 1 in 1.9. With chance association we would expect 1 in 2.1. The success rate for predicting earthquakes using the 5-day window was 11 out of 35, i.e., 1 in 3.2. With chance association we would expect 1 in 3.3. Clearly, these figures suggest chance association between preseismic TT events and seismic activity. However, 7 out of 35 earthquakes occurred with a coseismic TT event, i.e., 1 in 5. With chance association we would expect 1 in 19. This

Table 2. Summary of Relation Between Seismic Activity in the Andes During 1990–1995 and the Terminator Time Method Using 10- and 5-Day Windows

Year	Seismic Events	TT Events	Predicted (10 Day)	Predicted (5 Day)	Coseismic
1990	2	15	0	0	2
1991	1	9	0	0	0
1992	9	15	5	4	2
1993	10	19	5	4	1
1994	8	17	3	0	0
1995	5	15	5	3	2
Total	35	90	18	11	7

is suggestive of a possible influence of the earthquake on the timing of minima, although there is a large proportion of seismic events with little or no effect. The coseismic events are possibily caused by trapped atmospheric pressure waves, which generate traveling ionospheric disturbances. These are known and expected consequences of earthquakes [*Johnston*, 1997]. No obvious common feature could be found between the seven earthquakes in question, either in depth, location, time of year, or magnitude.

A convenient way of testing for chance association is to randomize the times and locations of either the earthquakes or the times of the TT events. Such randomization should be done with care, because both the earthquakes and TT events have some statistical structure. A reasonable null hypothesis should preserve this structure [*Kagan and Jackson*, 1996]. The importance of including realistic clustering in the simulated earthquake data used to test prediction methods has been discussed by *Michael* [1997]. We randomized the timing of TT events by shifting all the TT data by first 1 year, then 2, up to 5 years offset, wrapping round from 1995 to 1990 where required. This provided five sets of randomized TT data with the statistical structure preserved. The number of seismic events that were successfully predicted by the five sets using a 10-day window were 14–20 (compare with 18 previously). This equates to a range of 1 in 1.7 to 1 in 2.5, thus showing that the actual result of 1 in 1.9 is within the range of the results from the randomized data and indistinguishable from the estimate of chance association, i.e., 1 in 2.1. Using a 5-day window gave 8–14 successful predictions (compare with 11 previously). Coincident events ranged from 2 to 7 (compare with 7 previously). Once again, the success rates of seismic precursors using the TT method cannot be distinguished from random chance association.

We have already mentioned that there is a question about the influence on VLF propagation of deep earthquake activity. The South American earthquakes are typically much deeper than the 30–50 km used as a cutoff threshold (see Table 1). Thus it is possible to suggest that a correlation between the majority of seismic activity in the Andes and TT changes would not be expected to occur. In this case, the level of false prediction using the TT method is high, to the extent that it could not be used in any meaningful way as a warning tool. Of the 35 earthquakes in the study, seven were shallower than 50 km. Three were successfully predicted using the 10-day window (1 in 2.3), three were predicted with the 5-day window (1 in 2.3), and one had a coseismic TT event (1 in 7). There is no clear increase in the occurrence of successful predictions when the study is limited to shallow earthquakes.

4. Summary

We have analyzed the changes in timing of modal minima generated by the passage of the sunrise terminator over the seismically active region in South America using signals from a distant VLF communication transmitter. The variations in timing throughout the year are of a size and occurrence frequency similar to those previously reported, i.e., ±0.5–1 hour and 1–2 per month for $>2\sigma$ events (TT events).

Analysis of all the data for the years 1990-1995 suggests chance association between preseismic TT events and seismic activity. Testing for chance association, we randomized the timing of TT events with the statistical structure preserved. The success rates of seismic precursors using the TT method could not be distinguished from randomized data. Of the 35 earthquakes in the study, seven were shallower than 50 km. However, there was no clear increase in the occurrence of successful predictions when the study was limited to only shallow earthquakes, and the level of false prediction was high.

Previous studies using the terminator time method have used transmissions from the Omega network on a short (1 Mm) path and using 10- to 14-kHz signals. With the closure of the Omega system it would appear natural to continue the same studies using signals from VLF communication transmitters in the range 16-28 kHz. However, our analysis of 24-kHz signals indicates that the occurrence rate of successful earthquake predictions using the terminator time method cannot be distinguished from that of chance, and hence it is unlikely that these kind of measurements could have any useful predictive power.

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