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On the Spatial Relationship Between Lightning Discharges and Propagation Paths of Perturbed Subionospheric VLF/LF Signals

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A study has been made of the spatial relationship between propagation paths of subionospheric VLF/LF signals exhibiting sudden amplitude perturbations (Trimpi events) and time correlated cloud-to-ground lightning flashes. On each of the 4 days examined the storm centers were located close to the signal path from the NAU transmitter (28.5-kHz) in Puerto Rico to Stanford (SU) and were at large distances from the propagation path of the 48.5-kHz transmitter signal from Nebraska to SU. Nevertheless, no Trimpi events were observed on the former path, while many were seen on the latter. Furthermore, the detected Trimpi perturbations of the 48.5-kHz signal received at Stanford were found to be associated with the lightning activity in the distant storm centers. Since the NAU-SU path lies entirely at $L < 2$ and the 48.5-SU path is located mostly at $2 < L < 3$, the L dependent magnetospheric conditions which determine the level of lightning-induced electron precipitation are different along the two paths. Thus we postulate that the observed difference in Trimpi occurrence on the two paths was due to the different magnetospheric conditions. Hence the occurrence of Trimpi events over the geographical region corresponding to $L < 3$ may be more dominantly controlled by magnetospheric conditions than the source lightning distribution.

1. INTRODUCTION

As a result of gyroresonant pitch angle scattering by lightning-generated whistler waves, energetic electrons in the radiation belts are precipitated into the ionosphere at D region altitudes. The resultant secondary ionization in the ionosphere leads to transient perturbations of subionospheric VLF/LF signals known as Trimpi events, characterized by an abrupt (~1-s) change in amplitude and/or phase of the signal followed by a slow (~10-100-s) recovery [*Helliwell et al.*, 1973; *Lohrey and Kaiser*, 1979]. Most previous works on Trimpi events have concentrated on their association with ducted whistlers [*Inan and Carpenter*, 1986], their occurrence statistics and geographic distribution [*Carpenter and Inan*, 1987; *Inan et al.*, 1988*a*], and their association with patches of secondary ionization [*Dowden and Adams*, 1988; 1989; *Poulsen et al.*, 1990]. With the establishment of nationwide lightning detection networks, continuous data on lightning activity in the continental U.S. have recently become available. This provides us with the capability of relating Trimpi events to individual lightning discharges. Hence it is now possible to investigate the relationship between the spatial distributions of lightning discharges and of Trimpi events.

A first study of the spatial relationship between lightning discharges and the great circle propagation paths (GCPs) of the subionospheric VLF/LF signals exhibiting Trimpi events was recently conducted in the case of an isolated storm located off the east coast of the United States [*Inan et al.*, 1988*b*]. Figure 1 presents some of the data used in the study. The specifics of the four VLF/LF signals examined are detailed in Table 1. During the hour of 0500 UT on March 13, 1987, a storm center was found to be located within 150 km of the GCP of the NAU signal to Lake Mistissini (LM), Quebec (50°N, 74°W, $L \simeq 4.9$). The GCPs of the other three signals received at LM were at considerable distances from the same storm location. Meanwhile, of the four VLF/LF signals monitored at LM, NAU had numerous Trimpi events, including some with >10% changes in amplitude, while the other three had none at all (Figure 1*a*). Further analysis of the data led to Figure 1*b* which suggests that lightning flashes closer to the GCP of a subionospheric VLF/LF signal may be more effective in producing Trimpi events. This result appears to imply that the locations of lightning discharges with respect to the GCP of a subionospheric VLF/LF signal could be a controlling factor in the occurrence of Trimpi events on that signal. However, the importance of the locations of lightning discharges relative to other factors such as magnetospheric conditions is yet to be examined.

In an attempt to investigate the relative importance of lightning location in the occurrence of Trimpi events a study was undertaken of the spatial relationship between lightning discharges and VLF/LF signal amplitude perturbations in four different time periods in October and November of 1987. The results are quite different from those of *Inan et al.* [1988*b*], and they suggest that when lightning activity is located at lower L shells ($L < 2$), magnetospheric conditions may be a more dominant controlling factor than lightning location in the occurrence of Trimpi events.

2. DESCRIPTION OF DATA

The VLF/LF data used in this study were acquired at Stanford (SU), California (37°N, 122°W, $L \simeq 1.8$) during the period of October-November 1987. The data consist of simultaneous high resolution measurements of the amplitudes and phases of VLF/LF signals originating at various locations in the northern hemisphere during local night-time hours corresponding to ~0100-1500 UT. The amplitudes of the signals were measured using narrow-band receivers with a 3-dB full bandwidth of ~300 Hz. The envelopes of the receiver outputs were initially sampled at a rate of 100 Hz and subsequently recorded on digital tape at 20 or 50 Hz,

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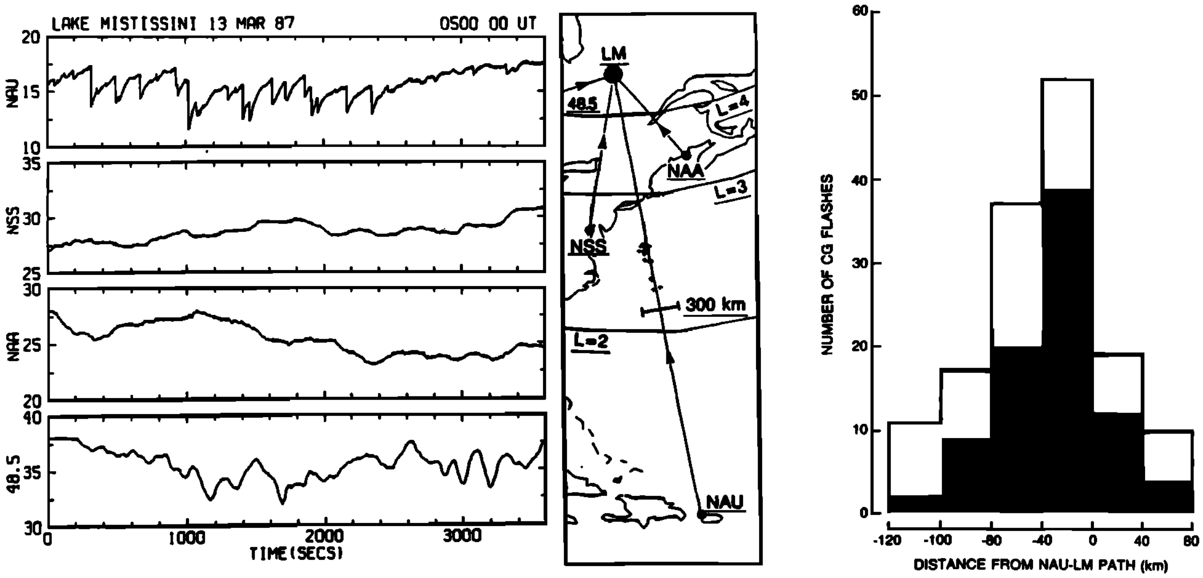

(a) (b)

Fig. 1. (*a*) Amplitude variations of four different VLF/LF signals observed at Lake Mistissini, Quebec, during 0500 UT on March 13, 1987. The great circle propagation paths are shown on the right. The locations of CG lightning flashes detected during this period are shown on the map as pluses. The signal amplitudes were all measured within a ~ 300-Hz bandwidth and averaged over ~1-s. (*b*) Distribution of CG flashes in terms of distance of flash location from the NAU-LM great circle propagation path. The solid lines represent all CG flashes, whereas shading shows only those time correlated with Trimpi events on NAU. These figures are reproduction of Figure 19 and Figure 9 respectively from *Inan et al.* [1988*a*]. They serve to summarize the results of a related spatial relationship study in that paper.

TABLE 1. List of VLF/LF Transmitters

Transmitter	Location	Latitude	Longitude	Frequency
NAA	Maine	45°N	67°W	24.0 kHz
NAU	Puerto Rico	18°N	67°W	28.5 kHz
NSS	Maryland	39°N	76°W	21.4 kHz
48.5	Nebraska	42°N	98°W	48.5 kHz

depending on the particular transmitter signal. Timing information was acquired from the GOES satellite with 1.5 ms accuracy.

For the purpose of this study, data on the amplitudes of the NAU, NSS, and 48.5 signals as received at SU were examined. Detailed comparison of the responses to lightning activity was done between the NAU and the 48.5 signals. While the NAU-SU and the 48.5-SU paths lie in different geomagnetic regions and thus provide a good basis for comparison of event occurrence in the range $L < 2$ (NAU-SU) versus $2 < L < 3$ (48.5-SU), the NSS signal was also examined in order to ensure that the differences between the NAU and the 48.5 signal responses observed in this study were not due to the higher frequency of the latter. The fact that some of the events identified on the 48.5 signal were also observed on the NSS signal, while none were seen on the NAU signal indicates that the different responses of NAU and 48.5 could not be entirely attributed to their frequency difference. Of course, the difference in frequency between NSS and 48.5, and the different relative locations of particular disturbed ionospheric regions with respect to the transmitters of the two signals, may lead to different sensitivities of their amplitudes as received at SU to perturbations of the Earth-ionosphere waveguide [*Poulsen et al.*, 1990], possibly leading to the less frequent occurrence of Trimpi events on NSS than on 48.5.

The lightning data were acquired by the SUNY-Albany (SUNYA) the National Severe Storms Laboratory (NSSL), and the Bureau of Land Management (BLM) lightning detection networks. The geographical coverage of the three networks combined together spanned most of the continental U.S.. By design the lightning detection systems employed by the networks recorded cloud-to-ground (CG) flashes only; intracloud (IC) flashes were ignored. In addition, the networks typically detect only 70% of the CG flashes within their area of coverage. These limitations are reflected in the fact that not all the observed Trimpi events were time correlated (as defined in the next section) with some flashes in the lightning data. A detailed description of the operating principles of the SUNYA network is provided by *Orville et al.* [1987].

The lightning data provide, among other things, the time of occurrence, the latitude and longitude, and the peak current in the first return stroke of each detected flash. A positive peak current corresponds to positive charge being lowered to the ground. The peak current information is used in this study as a measure of the intensity of the flash. Uncertainty in flash location was ~10 km. Timing accuracy depends on the locations of the flashes with respect to the 104°W meridian. Flashes located east thereof were recorded by the SUNYA and the NSSL networks with 1-ms accuracy; flashes located west thereof were recorded by the BLM network with unknown accuracy. Consequently, even though all the data from the three networks are shown in all of the figures indicating lightning activity, time correlation of individual flashes with Trimpi events could be established only when the flashes were located east of the 104°W meridian.

3. METHODOLOGY

The starting point of our joint analysis of VLF/LF and lightning data was 1-hour plots of the amplitudes of the NAU, NSS,

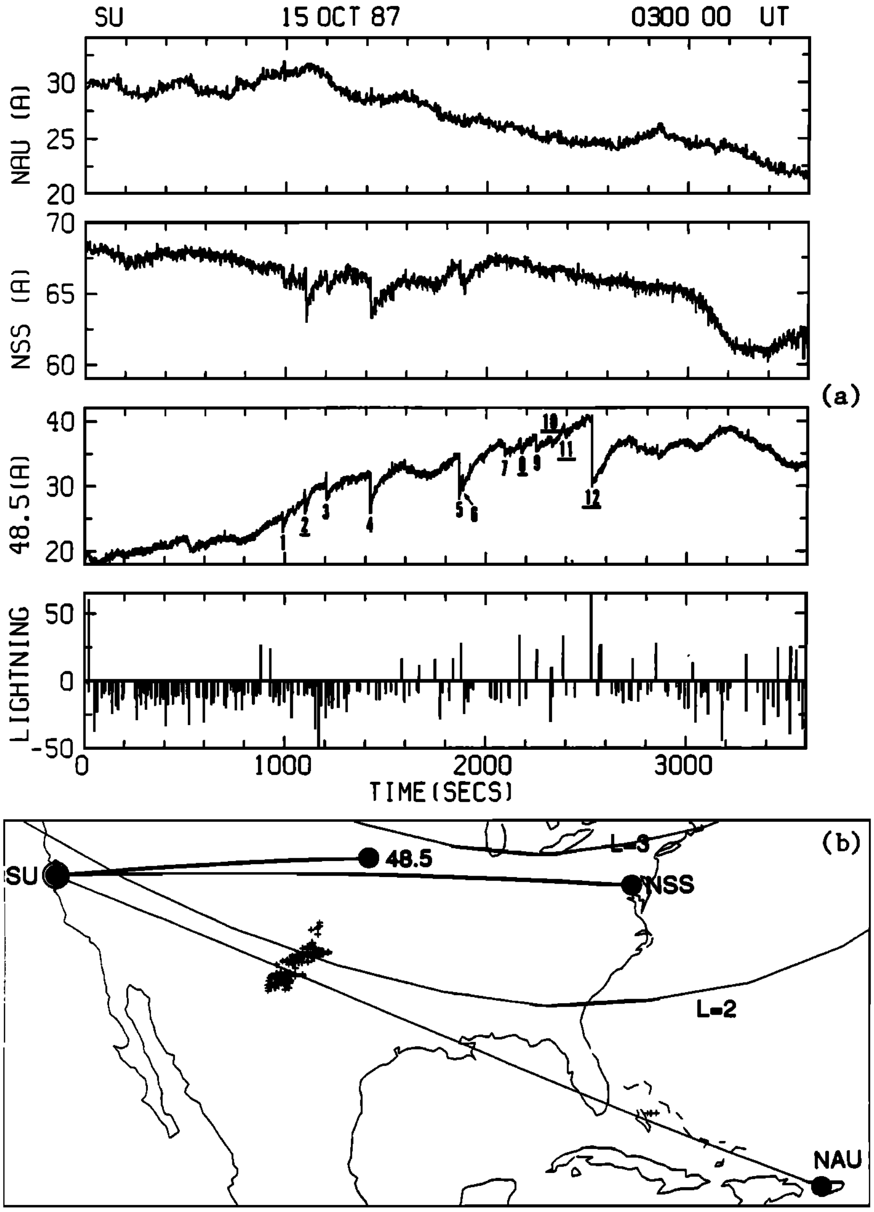

Fig. 2. (*a*) Comparison of VLF/LF activity recorded at SU with CG lightning activity during 0300 UT on October 15, 1987. The top three panels display the amplitudes A of the 28.5-kHz NAU, the 21.4-kHz NSS, and the 48.5-kHz signals averaged over 2.56, 1.28, and, 0.64 s, respectively. All amplitudes are in linear arbitrary units of percentage of full scale, with A=0 representing the absence of the signal, and are measured within a bandwidth of ~300 Hz. Trimpi events detected on the 48.5-SU path are numbered for reference in the text and in Figure 3. Those events which are time correlated with CG flashes are marked with an underscore. A CG flash is defined to be time correlated with a Trimpi event when it occurred within 1s prior to the event onset. The fourth panel shows the time of occurrence and the intensity of all the CG flashes recorded by the SUNYA, the NSSL, and the BLM lightning detection networks. Both positive and negative flashes are shown. The intensity is displayed as percentage with 100% corresponding to a peak current of 400 kA in the first return stroke of the flash. A positive peak current means that positive charge was lowered to the ground. The time t=0 corresponds to the UT given in the upper right corner. (*b*) Locations of individual CG flashes detected during 0300 UT on October 15, 1987, with respect to the great circle propagation paths of NAU-SU, NSS-SU, and 48.5-SU. The loci of the footprint of the L =2 and 3 geomagnetic field lines at 100 km altitude are also shown.

and 48.5 signals as observed at SU. These plots were visually inspected for Trimpi events, which are specifically defined here to be changes in amplitude of >1% within ~1-s followed by a recovery to preevent level within ~10-100-s. Except in the fourth case study each event was subsequently displayed together with simultaneous lightning data with high time resolution. The display was then used to identify any time correlated CG flashes detected by the lightning detection networks. For the purpose of this study, a CG flash was defined to be time correlated with a Trimpi event when it occurred within 1 s prior to the event onset. (Event onset is used here to refer to the instance when the amplitude change commences.) No distinction was made between events in which the lightning preceded the event onset by an observable fraction of a second, as expected in the case of electron precipitation resulting from scattering by lightning-induced gyroresonant whistlers (LEP events) [*Chang and Inan*, 1985], and events in which perturbation onset occurred immediately (<50 ms) after the lightning discharge ("early/fast" events) [*Armstrong*, 1983; *Inan et al.*, 1988*b*]. In most cases, detailed analysis of well defined events indicated that they were of the former type.

As a measure of the proximity of a lightning flash to a specific VLF/LF signal propagation path, the shortest great circle distance from the flash location to the GCP of the signal was calculated using the lightning data. It is in terms of this distance that locations of individual flashes with respect to various GCPs were expressed in section 4.

Radio atmospherics (spherics) generated by both CG and IC flashes from around the world were detected by the VLF/LF receivers at SU. They appeared as short (<50 ms) spikes on the continuous waveform of the received signals. When the intensity of the VLF/LF signal in a particular channel was relatively low, these spikes were easily recognizable. Consequently, a channel receiving a weak VLF/LF signal could serve as a spheric detector. In this study the 28.5-kHz channel at SU was both examined for Trimpi events on the NAU signal and used to detect spherics. Spherics due to lightning flashes not recorded by the lightning detection networks, including missed CG flashes, ignored IC flashes, and all lightning flashes outside the total coverage area of the lightning detection networks, could also be detected by this 28.5-kHz receiver. However, in this study the spheric data from the 28.5-kHz channel were used solely to confirm the timing of the lightning data.

4. RESULTS

In this section we describe in detail the analysis of 1-hour data from four different days during the period of October-November 1987.

Case 1: October 15, 1987, 0300 UT

The amplitudes of NAU, NSS, and 48.5 together with the intensity of individual lightning flashes for the hour of 0300 UT on October 15, 1987, are displayed in Figure 2*a*. Events on the 48.5-SU path are numbered in order; those with one or more time-correlated lightning flashes detected by the networks are marked by an underscore. No Trimpi events were observed on NAU, while both NSS and 48.5 were perturbed. A total of 12 events were identified on the 48.5 signal.

Figure 2*b* shows the location of all CG lightning flashes that were recorded within the coverage area of the detection networks during the same time period. There was a single storm center east of the 104°W meridian with 236 CG flashes recorded in this hour. All CG flashes were located within 400 km of the NAU-SU GCP but were more than 400 km from the 48.5-SU GCP.

In Figure 3, six of the 12 events on 48.5 are shown with expanded time resolution. Each plot spans 10-s around an event onset. Simultaneous plots of the lightning and the output of the 28.5-kHz channel are also shown for identification of time-correlated lightning flashes.

For event 2, a time correlated CG flash could be identified in the lightning data. The 28.5-kHz channel also detected three spherics within 1-s prior to the event onset, none of which corresponded to the time correlated CG flash. In any case, the time correlated

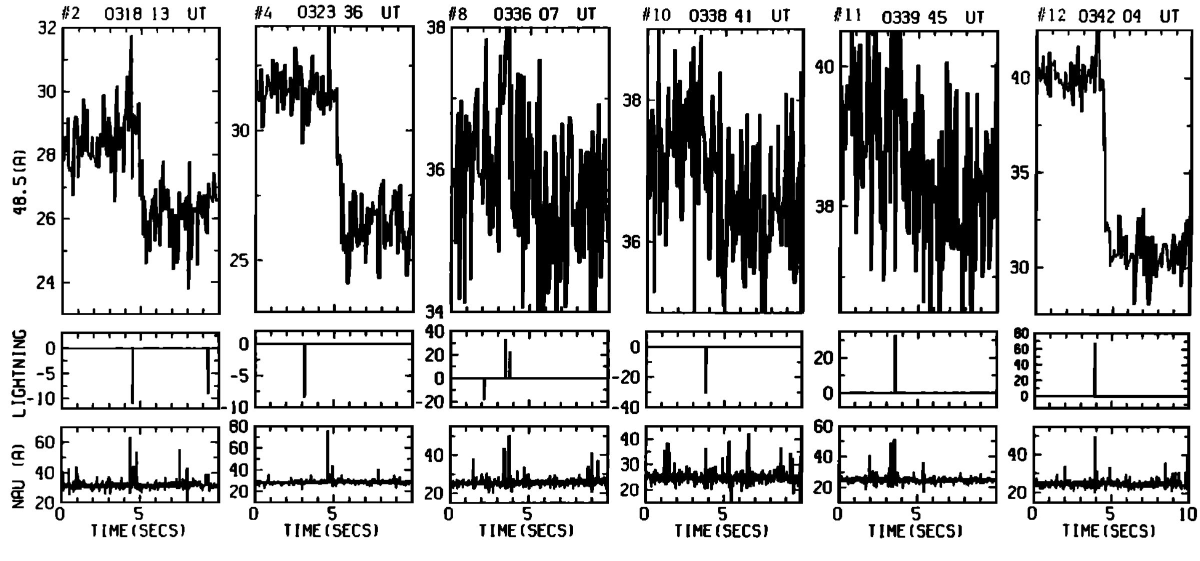

Fig. 3. Temporal comparison of six of the 12 Trimpi events identified on the 48.5-SU path with CG flashes recorded by the lightning detection networks and with radio atmospherics detected at SU on the 28.5-kHz channel during 0300 UT on October 15, 1987. The top set of panels display the amplitude of the 48.5-kHz signal averaged over 0.08 s during the 10-s periods centered around the Trimpi events. The number at the upper left corner of each panel corresponds to the event number in Figure 2. Except for event 4, every event was preceded by a CG flash by <1 s. The middle group of panels show the time of occurrence and the intensity of the CG flashes recorded during the corresponding time periods. The timing accuracy of these lightning data is 1 ms. The bottom panels display the received signal amplitude at SU in a ~300 Hz bandwidth centered at 28.5-kHz, the operating frequency of the NAU transmitter. Since the NAU signal amplitude was relatively low, radio atmospherics generated by lightning flashes including those not recorded by the lightning-detection networks could appear as easily recognizable sharp spikes. However, depending on the energy spectrum of the lightning flash, sometimes it may not register. For instance, the CG flash at ~ 0323 : 39 UT and the one at ~0336:09 UT did not correspond to any spikes on the output of the 28.5-kHz receiver. The base level at arbitrary unit of $A \simeq 30$ represents the NAU signal level. The time $t = 0$ corresponds to the UT given at the upper right corner of each column of panels. The UT is accurate to within 10 ms.

CG flash could have coincidentally occurred within 1-s prior to the Trimpi event onset. However, through sufficiently repeated observation of time correlated CG flashes and Trimpi events it is possible to support a cause-and-effect relationship between the former and the latter. The conditions of sufficiency will be established on a probabilistic basis in the next section.

Event 4 is an example in which no time correlated CG flashes were recorded by the networks. Nevertheless, a possible causative spheric was present on the NAU channel and was also seen superimposed on the 48.5-kHz signal. As an aside, both the second and the third CG flashes recorded in the 10-s period centered around event 8 corresponded to a spheric on the 28.5-kHz channel. However, the intensities of these CG flashes were not in proportion to the amplitudes of the corresponding spherics. This suggests that the peak current in the first return stroke of a CG flash may not be a good measure of the energy radiated by the CG flash at a particular frequency.

The rest of Figure 3 shows the four other examples in which a time correlated CG flash was detected. Overall, a total of five out of the 12 events in the hour of 0300 UT had time correlated CG flashes.

Case 2: November 8, 1987, 1000 UT

Data from the hour of 1000 UT on November 8, 1987, are shown in Figures 4 and 5 in the formats of Figures 2 and 3, respectively. Two major storm centers could be identified on this day, one centered around the NAU-SU GCP, the other in between the NAU-SU and the NSS-SU GCPs. A total of 298 CG lightning flashes were recorded in this hour from the two storm centers. The

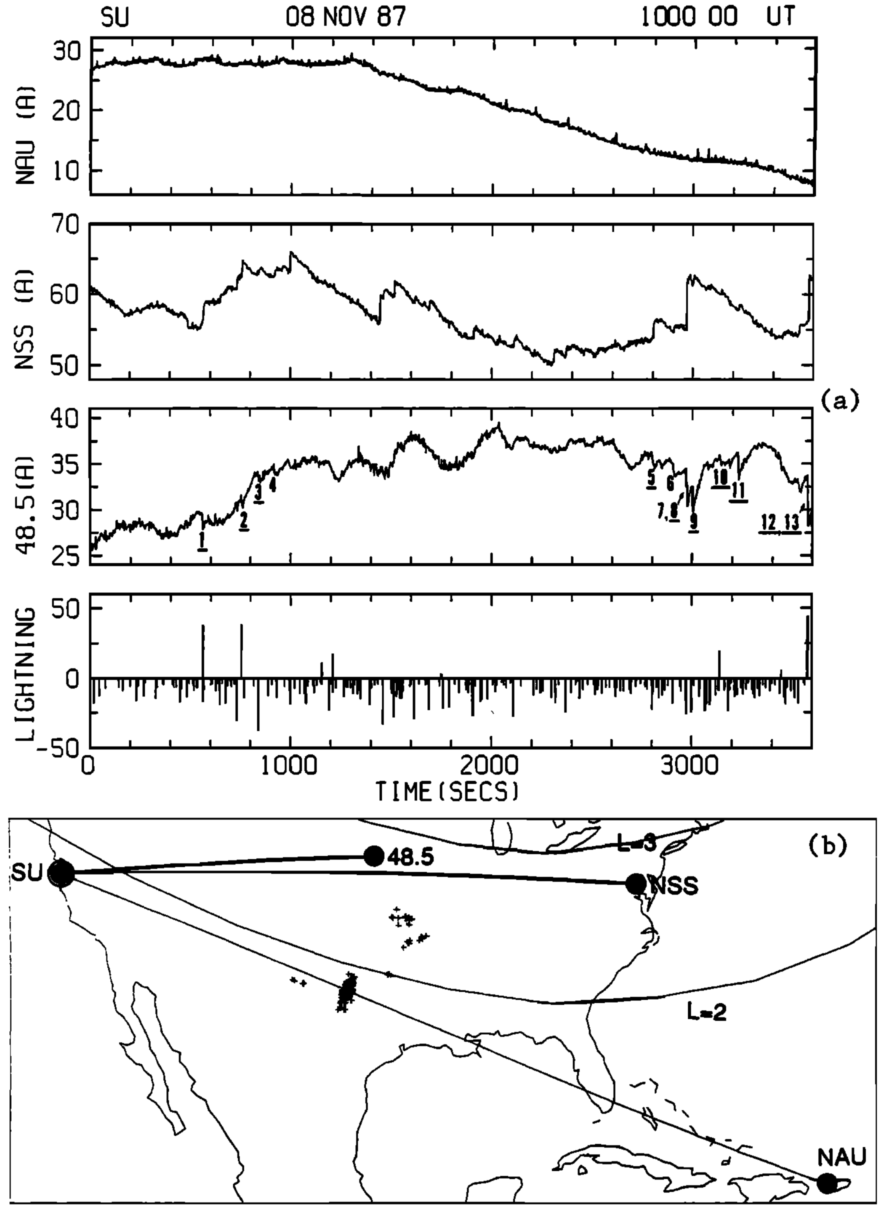

Fig. 4. Comparison of VLF/LF activity recorded at SU with CG lightning activity detected during 1000 UT on November 8, 1987. The formats of the figures are identical to those of Figures 2*a* and 2*b*, respectively, except that the amplitudes of all of NAU, NSS, and 48.5 were averaged over 2.56-s in Figure 4*a*.

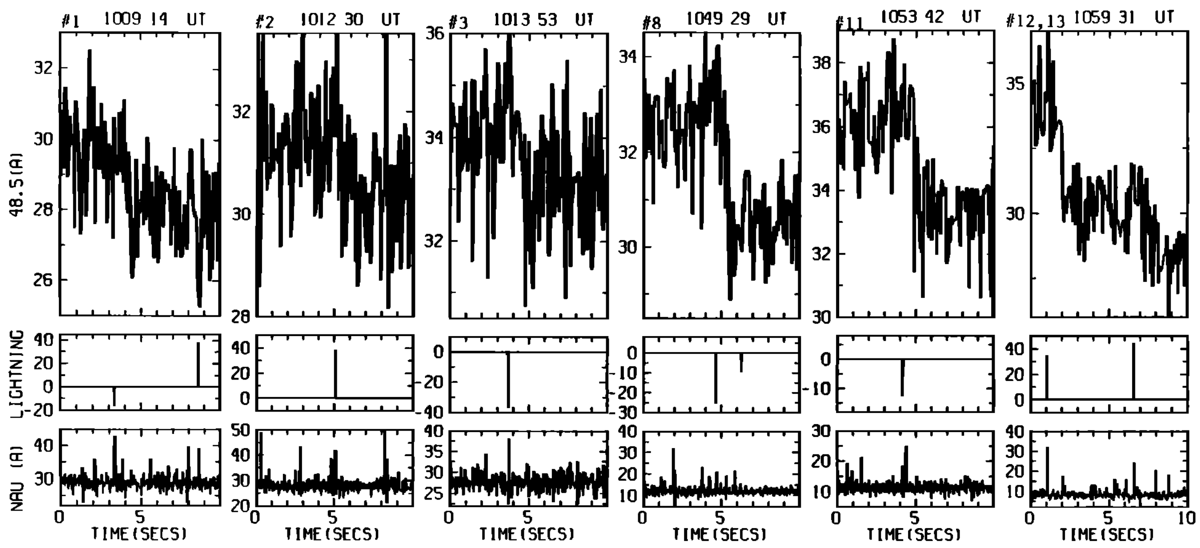

Fig. 5. Temporal comparison of 6 of the 13 Trimpi events detected on the 48.5-SU path with CG flashes recorded by the lightning detection networks and with radio atmospherics detected at SU by the 28.5-kHz channel during 1000 UT on November 8, 1987. The format of the figure is identical to that of Figure 3. These 6 events are selected as the most well defined out of the 10 events which are time correlated with CG flashes.

majority (~260) of the flashes were located around the first center and were within ~200 km of the NAU-SU GCP and >800 km from the 48.5-SU GCP. Flashes in the second center lay within ~400-700 km of both the NAU-SU and the 48.5-SU GCPs. The 1-hour plots again revealed no Trimpi events on NAU but some Trimpi events on NSS. On 48.5 there were 10 events accompanied by time-correlated CG flashes out of the 13 events identified. The most prominent six of the correlated events are shown with expanded time resolution in Figure 5.

Case 3: November 15, 1987, 1000 UT

The third data set is from the hour of 1000 UT on November 15, 1987, and is displayed in Figures 6 and 7, again in the formats of Figures 2 and 3, respectively. This was an hour of high lightning activity with a total of 578 CG flashes detected. Flash locations were mostly within 350 km of the NAU-SU GCP, yet no Trimpi events were observed on NAU. On the other hand, although most of the flashes were more than 700 km from the 48.5-SU GCP, 22 Trimpi events were registered on the 48.5 signal. A total of sixteen out of these 22 events were accompanied by time correlated CG flashes; the six most prominent of these 16 events are shown on an expanded time scale in Figure 7. Incidentally, there were no Trimpi events on NSS in this hour.

Case 4: November 6, 1987, 0600 UT

Most of the lightning flashes in the hour of 0600 UT on November 6, 1987, were located west of 104°W. As a result, the timing information of the lightning data is unreliable, as explained in section 2. Hence simultaneous plots of the VLF/LF and lightning data would be misleading. Therefore Figure 8*a* displays only the amplitudes of the three VLF/LF signals observed in this hour. Figure 8*b* shows the locations of the concurrent CG flashes in the same fashion as in Figure 2*b*. The 118 recorded CG flashes were mostly within 400 km of the NAU-SU GCP but more than 700 km from the 48.5-SU GCP. Prominent Trimpi events abound on both the NSS and the 48.5 signals. One or two Trimpi-like fluctuations of the NAU signal amplitude could also be identified. However, these fluctuations were less than 1% in amplitude and hence did not meet the requirements of our definition of an event as described in section 3.

5. DISCUSSION AND CONCLUSIONS

The individual associations of CG flashes with Trimpi events in Figures 3, 5, and 7 were established solely on the basis of the temporal relationship between the lightning flashes and the Trimpi events. As flash counts increase, it becomes more probable that a CG flash will occur within 1-s prior to the onset of a Trimpi event and yet be physically unrelated to the event. On the basis of a Poisson model for the occurrence of lightning flashes, estimates were made of the probability that repeated alignments in time to within 1-s of individual Trimpi events and their time correlated CG flashes had occurred by chance in each of the first three cases. Successive alignments were treated as statistically independent events. The probabilities are 5.15×10^{-4} for case 1, 2.23×10^{-9} for case 2, and 1.56×10^{-9} for case 3. Thus it is highly unlikely that the time-correlated CG flashes were physically unrelated to the Trimpi events. We also note that in most of the cases analyzed with high time resolution the time-correlated CG flashes preceded the Trimpi event onsets by 0.2-1-s, consistent with the time delay expected of LEP events [*Chang and Inan*, 1985]. Consequently, even though our lightning data coverage was not complete in global terms, we could at least attribute some of the observed Trimpi events on 48.5 in the first three of our four case studies to their time correlated CG flashes in the available lightning data.

Figure 9 shows the locations of all the CG flashes which were time correlated with Trimpi events on 48.5 in cases 1, 2, and 3. When more than one flash were time-correlated with an event, all such flashes were included. It is apparent from this figure that the majority of the CG flashes time correlated with Trimpi events on 48.5 were much more distant from the 48.5-SU path than from the NAU-SU path. Specifically, they were more than ~400-1100 km from the 48.5-SU path while being within ~0-650 km of

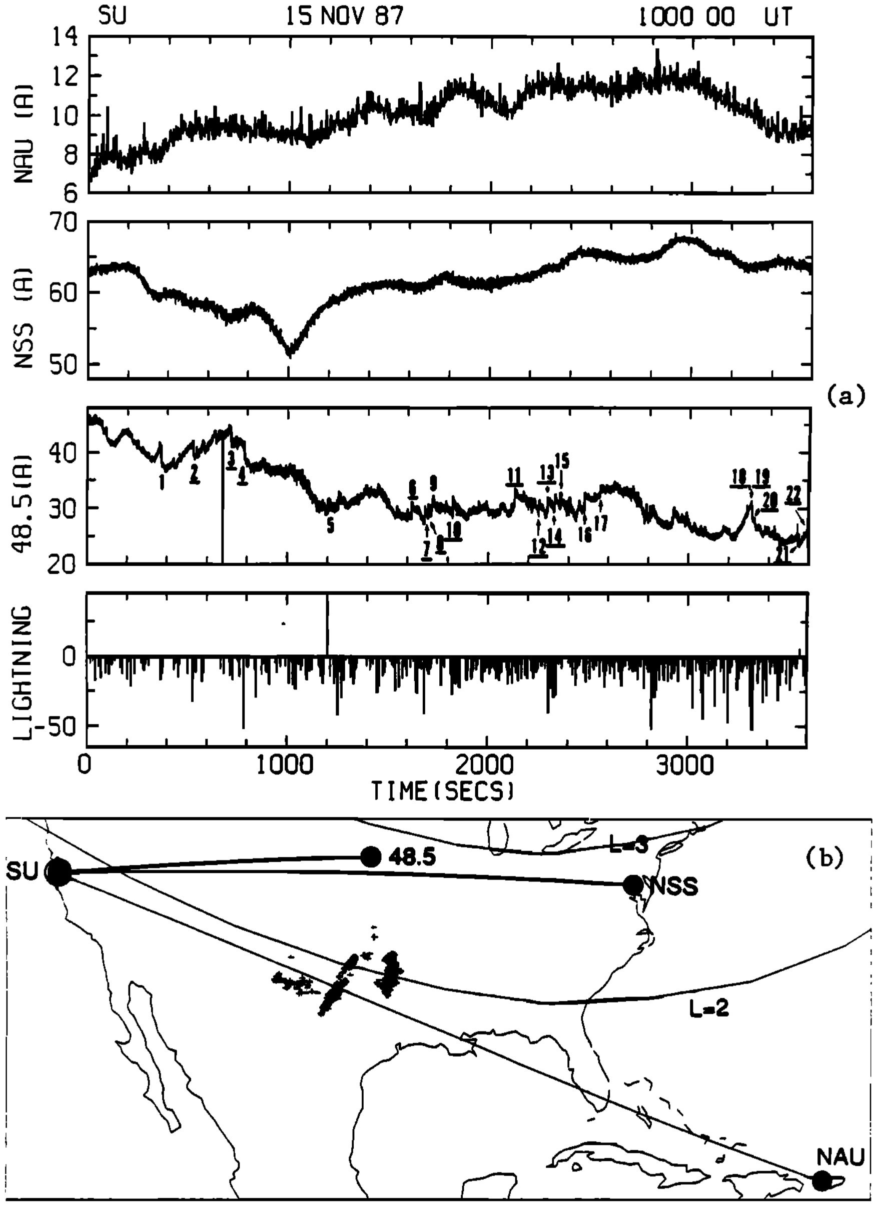

Fig. 6. Comparison of VLF/LF activity recorded at SU with CG lightning activity detected during 1000 UT on November 15, 1987. The formats of the figures are identical to those of Figures 2*a* and 2*b* respectively, except that the amplitudes of NAU, NSS, and 48.5 were averaged over 2.56, 0.64, and, 0.32 s, respectively.

the NAU-SU path. Nevertheless, they did not produce a single Trimpi event on NAU as received at SU. This result indicates that the GCPs of subionospheric VLF/LF signals perturbed by lightning-induced electron precipitations do not necessarily lie in the vicinity of the causative lightning discharges. It thus appears that the occurrence of Trimpi activity over various geographical regions may be more dominantly controlled by factors other than the source lightning distribution.

We note again that the difference in response of the NAU-SU versus the 48.5-SU paths to the same lightning activity is not likely to be due to the frequency difference between the two signals, since the NSS-SU path also registered some of the events on the 48.5-SU path. In fact, some of the Trimpi events on the NSS-SU path were also time correlated with CG flashes. Examples are the event at 0318:17 on October 15, 1987, and the events at 1025:14 and 1049:26 on November 8, 1987. The corresponding time-correlated CG flashes were at respectively 190, 45, and 28 km from the NAU-SU path while being at 550, 860, and 800 km from the NSS-SU path. In other words, they were close to the former path and remote from the latter. Furthermore, a few CG flashes which were time correlated with Trimpi events on the 48.5-SU path were also time correlated with Trimpi events on the NSS-SU path. Examples are the CG flash at 0318:17 on October 15, 1987, and the one at 1049:33 on November 8, 1987. These two CG flashes were again both close to the NAU-SU path and remote from the 48.5-SU and the NSS-SU paths. Hence the same results would have been obtained if the study had been conducted using the NAU-SU and the NSS-SU paths instead.

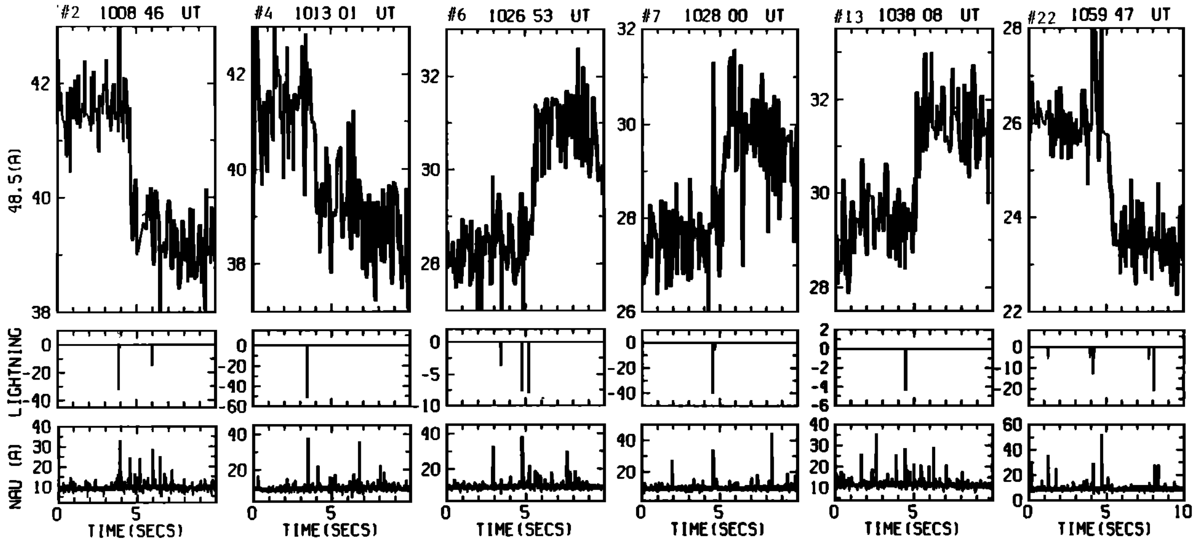

Fig. 7. Temporal comparison of six of the 22 Trimpi events detected on the 48.5-SU path with CG flashes recorded by the lightning detection networks and with radio atmospherics detected at SU by the 28.5-kHz channel during 1000 UT on November 15, 1987. These events are the most well defined amongst the 16 events which are time correlated with CG flashes. The format of the figure is identical to that of Figure 3.

However, the conclusions could not have been established with as much confidence since the Trimpi event count was lower on the NSS-SU path than on the 48.5-SU path. Since the frequency of NSS is lower than that of NAU, yet in this study the NSS-SU path exhibited qualitatively similar response to the same lightning sources as the 48.5-SU path, the observed difference between the NAU-SU and the 48.5-SU paths was not likely to be attributable to the lower frequency of the former signal.

Another difference between the NAU-SU and the 48.5-SU paths is the L shell range, apparent from Figure 2*b*. A combination of magnetospheric factors may have rendered the region of $2< L <3$ (in which most of the 48.5-SU path lies) more favorable for the occurrence of Trimpi events than the region of $L <2$ (of the NAU-SU path). Magnetospheric conditions such as the availability of ducts for efficient propagation and guiding of whistler waves injected by lightning (important in the case of Trimpi events produced by ducted whistlers), the distribution of trapped energetic electron in the radiation belt [*Inan et al.*, 1989], and the efficiency of wave-induced pitch angle scattering as a function of L shell [*Chang and Inan*, 1985] are all examples of factors important for the occurrence of Trimpi events.

The geomagnetic activity as measured by $\sum Kp$ varied for the four cases studied ($\sum Kp$=31, 18, 9, and 23, respectively). The corresponding locations of the plasmapause would all be expected to have been at $L >3$ [*Carpenter and Park*, 1973]. Previous work on the occurrence statistics of Trimpi events has shown little or no correlation with geomagnetic activity [*Carpenter and Inan*, 1987], although it is possible that injection of particles that sometimes accompanies increased geomagnetic activity may play a role in Trimpi event occurrence under certain conditions (J. V. Rodriguez et al., A case study of lightning, whistlers, and associated ionospheric effects during a substorm particle injection event, manuscript in preparation, 1990).

CG lightning discharges can indeed excite ducted whistler paths with endpoints distant (>2500 km) from the lightning locations [*Carpenter and Orville*, 1989]. Moreover, findings of both *Chang and Inan* [1985] (based on theoretical modeling) and *Carpenter and Inan* [1987] (based on experimental data) indicate that there is a high level of whistler-induced electron (with energy >40 keV) precipitation in the range $2 < L < 3$. (Incidentally, the comparisons in both studies were between precipitation occurrence in the range $2< L <3$ and occurrence at higher latitudes, not that at $L <2$). On this basis, lightning activity at a distance of up to >1100 km from the 48.5-SU path (lying mostly in the $2< L <3$ range) could cause Trimpi perturbations of the 48.5-kHz signal. However, the high level of Trimpi activity on the 48.5-SU path far from the lightning sources, compared to the complete absence of Trimpi events on the NAU-SU path in the vicinity of the lightning sources may not have been expected. It suggests that magnetospheric conditions are at times more important than the proximity of the lightning discharges in determining the level of Trimpi activity on a particular subionospheric VLF/LF propagation path.

To interpret the results of *Inan et al.* [1988*b*] as summarized in Figure 1 in light of our present study, we note that the isolated storm in the case of March 13, 1987, was located in the $2< L <3$ range. Thus the CG flashes occurred in a region where magnetospheric conditions were likely to be favorable for the occurrence of Trimpi events. Furthermore, it is observed that CG flashes closer to the NAU-LM path were more likely to be time correlated with Trimpi events on the path (Figure 1*b*). This importance of the proximity of the lightning flashes to the signal GCP in determining the level of Trimpi activity may have become noticeable under the favorable magnetospheric conditions around the flashes. Hence the rate of Trimpi event occurrence may depend on the proximity of source lightning flashes when the magnetospheric conditions around the lightning flashes are generally favorable for propagation of whistler waves and for the whistler-induced precipitation of energetic electrons.

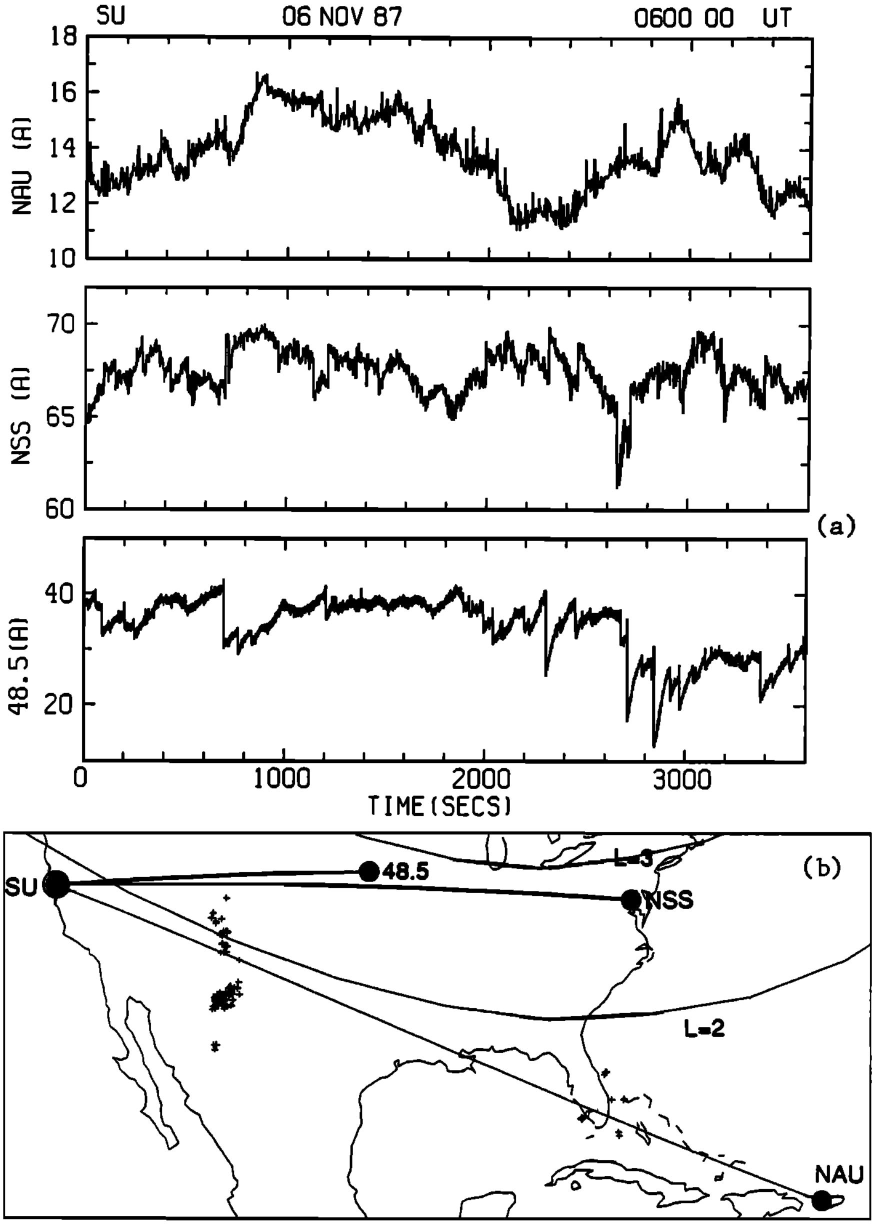

Fig. 8. (*a*) VLF/LF activity recorded at SU during 0600 UT on November 6, 1987. The format of each panel is the same as that of the corresponding panel in Figure 2*a* except that the amplitudes of NAU, NSS and 48.5 were averaged over 2.56, 1.28, and, 0.32 s, respectively. (*b*) Locations of individual CG flashes detected during 0600 UT on November 6, 1987, in the same format as Figure 2*b*.

In conclusion, even though previous study [*Inan et al.*, 1988*b*] indicates that the location of lightning activity could be a controlling factor in the occurrence of Trimpi events, our present study suggests that magnetospheric conditions may be more important in the $L < 3$ range.

As a final remark, we note that Trimpi events are in fact detected on the NAU-SU path, although not as common as on the 48.5-SU or NSS-SU paths. When observed on this relatively low L shell ($L < 1.8$) path, the events sometimes exhibit unusually rapid recovery signatures, which have been interpreted as being due to MeV electron precipitation induced by lightning [*Inan et al.*, 1988*c*]. Thus it is possible that Trimpi events at lower L shells occur under different conditions. Further analysis of data from the NAU-SU path, particularly in relation to lightning activity, may shed light on the conditions under which the NAU signal propagating along this path is perturbed.

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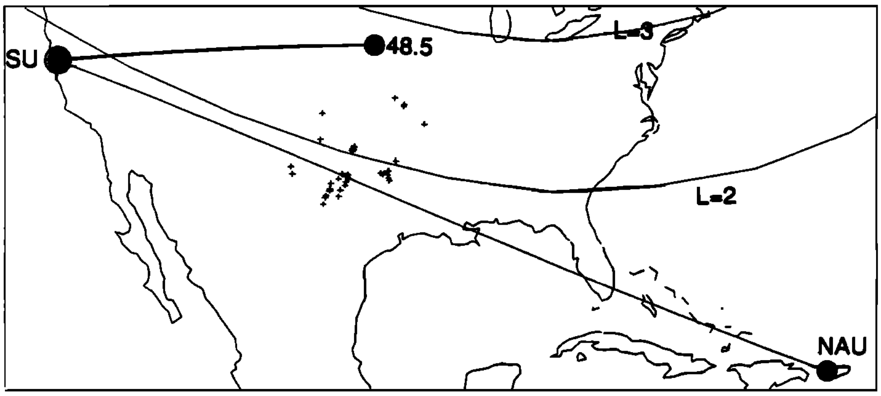

Fig. 9. Locations of all the CG flashes detected by the lightning detection networks which are time-correlated with Trimpi events observed on the 48.5-SU path during the hours of 0300 UT on October 15, 1987, 1000 UT on November 8, 1987, and 1000 UT on November 15, 1987. No Trimpi events were observed on the NAU-SU path at all during the same time periods. The locations of the great circle propagation paths of NAU-SU and 48.5-SU are shown to illustrate the relative distances of the flashes from the two paths. The loci of the footprint of the $L = 2$ and 3 geomagnetic field lines at 100 km altitude are also shown to locate the signal paths with respect to the L shells.

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