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Diurnal Variation of Burst Precipitation Effects on Subionospheric VLF/LF Signal Propagation Near L = 2

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Burst precipitation effects on subionospheric VLF/LF signal propagation are studied using data recorded at Palmer Station, Antarctica ($L \sim 2.4$) between March 3 and April 7, 1983. Relatively abrupt signal amplitude changes, known as "Trimpi" effects, were observed in conjunction with magnetospheric whistlers, which are inferred to induce electron precipitation that in turn causes enhanced ionization at the 80 to 90-km altitude level. Earlier findings that Trimpi effects occur predominantly under nighttime ionospheric conditions were confirmed by comparing the sunrise-sunset terminator position with perturbation activity on three VLF/LF signal paths for which the arrival bearings range from magnetic north to west. Events were found to occur on 70% of the observing nights. Signal paths making larger angles with the terminator were used to deduce that most events were caused by ionospheric effects occurring within ~1000 km of Palmer Station. Some events were observed after sunrise over the observing station, apparently due to precipitation in dark regions as far as ~1800 km away. Observed differences between two different paths in the occurrence of this postsunrise continuation of Trimpi events suggest that the Trimpi event activity rate decreases below $L \sim 2$. This may be due to a reduction in whistler activity and/or lower particle scattering efficiency. The average hourly occurrence rate of transmitter NSS events on the 11 most active nights studied increased from sunset to near midnight and then remained at a roughly constant level until sunrise. The influence of the whistler rate and of whistler path locations on Trimpi effects is clearly important and requires further study.

1. INTRODUCTION

In recent years there have been a number of studies of the 'Trimpi' effect, in which the amplitude or phase of a subionospherically propagating VLF signal is perturbed in one-to-one association with the reception of a magnetospheric whistler [*Helliwell et al.*, 1973; *Lohrey and Kaiser*, 1979]. Typical changes on paths 2000–10,000 km in length are found to be ~1–2 dB in amplitude and a few microseconds in phase delay. The changes typically develop within a time of ~1–2 s and decay over periods of ~10–100 s. Figure 1 shows examples of amplitude variations on three signals received at Palmer Station, Antarctica ($L \sim 2.4$). Arrows in the upper margin point to examples of changes that occurred simultaneously on all three signals (1, 2, and 3) or on at least two signals (4 and 5). The evidence indicates that most signal perturbations such as these are due to precipitation induced by whistlers, which scatter particles of sufficient energy and number to cause ionization density enhancements below 80 km altitude, the approximate reflection height for VLF waves under nighttime conditions in the earth-ionosphere waveguide.

The Trimpi phenomenon is known to occur under nighttime conditions [*Helliwell et al.*, 1973]; in the daytime the effect is presumably masked by the action of solar ultraviolet radiation, which lowers the VLF reflection height below the ~80–90 km altitude of the induced ionization enhancements and also substantially increases the background electron density in this altitude range.

The purpose of the present study is to investigate the effect of the sunrise-sunset terminators on Trimpi event activity and to use the results to help locate the precipitation regions. An equinoctial period was selected, to take advantage of seasonal peaks in occurrence of Trimpi events that have been reported during such periods [*Carpenter and LaBelle*, 1982].

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2. SOURCES OF DATA AND METHODS OF ANALYSIS

The data studied were recorded at Palmer Station, Antarctica, on eight-channel Sanborn charts and on magnetic tapes during the period March 3 to April 7, 1983. The charts include amplitude records of signals from a number of transmitters, as well as integrated VLF in the frequency bands 0.5–1.0 kHz and 2.0–4.0 kHz. Occurrences of Trimpi perturbations on the different signals were identified by visual inspection of the charts. The locations of the signal sources of interest and their operating frequencies are given in Table 1. The map of Figure 2 shows the great circle paths from the various transmitters to Palmer Station.

The magnetic tapes contain broadband VLF recordings for one 10-min or 12-min period each hour throughout the local night (typically 0150–1000 UT). Amplitude and phase recordings of selected transmitter signals were recorded on a separate track as voltage-controlled oscillator (VCO) outputs. Tapes were available for 19 nights during the March 3 to April 7, 1983, period. In the present study, data from the magnetic tapes were used primarily to obtain information on the whistler occurrence rate.

3. OBSERVATIONS

The daily occurrence rates of Trimpi events on the NSS, 37.2-kHz, and NPM signals during the period March 3 to April 7, 1983, are shown in Figure 3. Days of no detected events are marked by a zero. Trimpi events with relative amplitudes as low as 0.3–0.5 dB (depending on which signal is considered) were detectable by visual inspection of the charts. In some cases the presence of well-defined events on

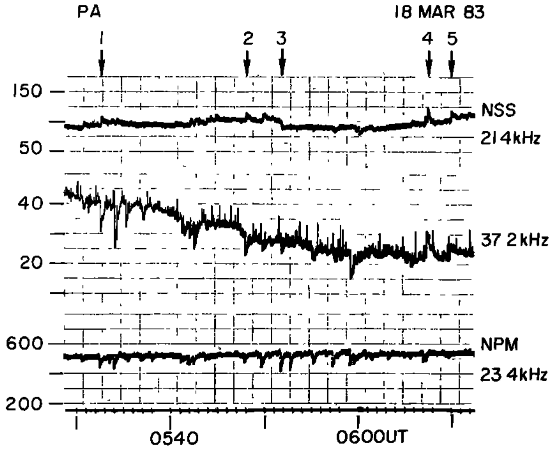

Fig. 1. Amplitude perturbations on three VLF/LF transmitter signals received at Palmer Station, Antarctica.

one transmitter signal was helpful in identifying simultaneously occurring but otherwise marginally detectable events on another signal.

Figure 3 shows that Trimpi events on NSS, 37.2 kHz, and NPM were detected on approximately 70% of the recording days and that the day-to-day occurrence patterns on the various signals were similar. A total of approximately 1000 events were detected on each of the signals.

In addition to the high day-to-day activity correlation, there was also a tendency for the majority of individual events to occur simultaneously on more than one signal. On many nights this was true of as many as 75% of the perturbations. In a few cases, events were observed to occur simultaneously not only on NSS, 37.2 kHz, and NPM, but also on Argentina Omega at 12.9 kHz (phase) and 780 kHz (Santa Cruz, Argentina) [*Carpenter et al.*, 1984].

Figure 3*a* shows the daily ΣKp values for the period of interest. There is no immediately obvious correlation; substantial Trimpi event activity occurred not only during the quiet period March 7–10, but also on March 12, 19, 21, 25, and 29, days exhibiting relatively high ΣKp or immediately following such days. Considering the amount of available statistics, these occurrence patterns are in rough agreement with the results of *Carpenter and LaBelle* [1982], who found that NSS perturbations at Palmer in September–October, 1978, occurred during and for days following major magnetic storms. In the present data, individual storms are less well defined, but a sensitivity to increases in disturbance activity is strongly suggested.

The occurrence rate of Trimpi events during the night varied widely from hour to hour. Detection of 20–30 events per hour was not unusual, and during peak activity over 50 events per hour were observed. These rates are consistent with those reported previously by *Helliwell et al.* [1973] and *Carpenter and LaBelle* [1982].

Trimpi events were mostly observed during either "nighttime" conditions, indicated by signal levels ~20–30 dB above daytime minima, or during transitions to and from nighttime levels. A few small events were detected on NPM under presunset conditions, with the signal level at ~20–80 μV/m as compared to the typical nighttime level of ~500 μV/m. Histograms of the UT of occurrence of the first and last Trimpi events of the night are shown in Figure 4. An arrow indicates the time of midnight over Palmer Station at 100 km altitude. The hours of occurrence of the first Trimpi event ranged on NSS from approximately 0000 to 1000 UT, on 37.2 kHz from 0200 to 0900 UT, and on NPM from 0100 to 0900 UT. The peak hours of occurrence of the first Trimpi event were at later hours for signals propagating over great circle paths that were further west.

Figure 4 shows that the Trimpi perturbations terminated within a range of times extending from 0500 to 1100 UT on NSS, from 0300 to 1100 UT on 37.2 kHz, and from 0600 to 1300 UT on NPM. These times are generally less widely distributed than those for the first Trimpi event of the night. On NSS and 37.2 kHz, the last detected perturbation of the night occurred most often between 0900 and 1000 UT, while on NPM it occurred between 0900 and 1100 UT. On average, the length of the period during which perturbations were detected was shorter for transmitters located further west. However, on a given night, the time between the first and last perturbations on a given signal ranged from less than 1 hour in some cases up to 11 hours in others.

The relationships of the three signal paths to the day/night terminator locations at 100 km altitude are indicated in Figure 5. Hourly terminator positions near sunset at Palmer on March 15 and April 1 are shown in Figures 5*a* and 5*c*, respectively, while Figures 5*b* and 5*d* provide the same information for times near sunrise. A comparison of the first- and last-event statistics of Figure 4 with Figure 5 indicates the following:

The first Trimpi event on NSS usually occurred after 0000 UT (Figure 4*a*). At this hour, darkness at 100 km altitude (Figures 5*a* and 5*c*) extended either all the way from NSS to Palmer or, in a few cases, to within a few hundred kilometers of the station. On 37.2 kHz (Figure 4*b*) the first events were observed only after 0200 UT, when darkness again prevailed over all of the path, with the possible exception of a small portion near the transmitter.

On NPM (Figure 4*c*), most of the first events of the night occurred after 0400 UT, when darkness either covered all of the path or that part of it extending from Palmer to near the geographic equator (Figures 5*a* and 5*c*). However, on seven of the nights the first event occurred prior to 0400 UT (Figure 4*a*), when darkness extended over lesser distances from Palmer along the great circle path. In these specific cases, the shortest estimated distance from Palmer to the terminator was ~1200 km.

Referring now to the last events of the night, on NSS

TABLE 1. List of Transmitters

Transmitter	Location	Latitude	Longitude	Frequency
NSS	Maryland	39°N	76°W	21.4 kHz
NPM	Hawaii	21°N	158°W	23.4 kHz
LF (37.2 kHz)	California	35°N	117°W	37.2 kHz
MF (780 kHz)	Argentina	50°S	69°W	780 kHz
Omega	Argentina	43°S	65°W	12.9 kHz

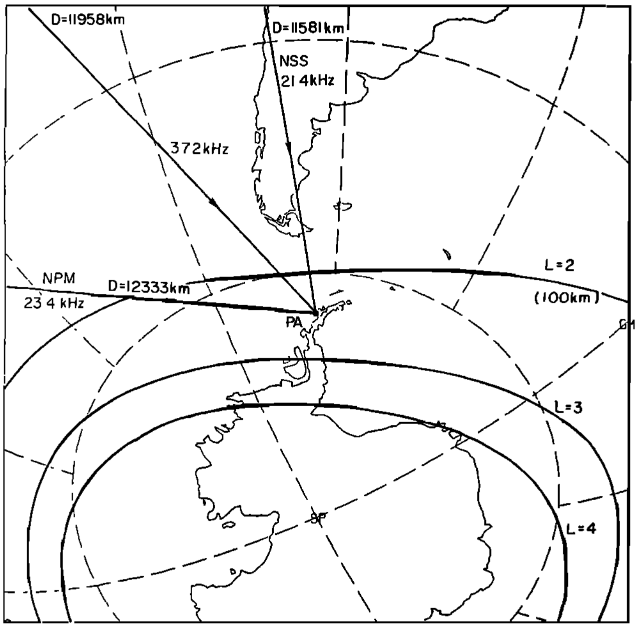

Fig. 2. Map showing portions of great circle paths from several VLF/LF signal sources to Palmer Station, Antarctica. *L* values at ~100 km altitude are indicated.

40% of these occurred between 0900 and 1000 UT (Figure 4*a*), which corresponds to sunrise in the vicinity of Palmer Station (Figures 5*b*, 5*d*). Several final events occurred after 1000 UT; in these specific cases most of the southern hemisphere portion of the NSS great circle path was in sunlight, but the terminator was within distances ranging from ~400 to 1600 km along the path to the west.

The final events on 37.2 kHz were also concentrated between 0900 and 1000 UT, as the great circle path from Palmer became sunlit to distances ranging up to ~1400 km. The few events on 37.2 kHz after 1000 UT occurred when the terminator was at distances of 1400 km or less along the path.

On NPM (Figure 4*c*), the final events of the night were concentrated between 0900 and 1100 UT. Most of this group of events occurred before the sunlit region had extended more than ~1000 km in the NPM direction. A few occurred later, with the terminator at a maximum range from Palmer of ~1800 km.

4. DISCUSSION

The evidence from Figures 4 and 5 that activity onsets are concentrated after sunset at Palmer and that terminations are concentrated near sunrise provides further indication that the Trimpi effect is essentially a nighttime phenomenon. The influence of the terminator position is clearly seen by noting that the mean duration of Trimpi activity depends on the angle between the terminator and the affected great circle path. For any phenomenon sensitive to full-path darkness, duration near the equinoxes would be expected to be maximum for a north/south path and minimum for an east/west path, since the entire length of the former is in darkness for a relatively long time, while the east/west path is in partial darkness for extended periods.

If we now assume that the ionospheric regions giving rise to the observed perturbations are located on the nightside of the 100 km altitude terminator, it is possible, using the results of Figures 4 and 5, to make crude estimates of the positions of the regions with respect to Palmer. Most of the final events on 37.2 kHz and NPM occurred before sunlight near Palmer had extended more than ~1000 km along the great circle paths involved. However, a few events were detected as sunlight extended further, to ~1400 km in the 37.2 kHz direction and ~1800 km in the NPM direction.

On NSS there were a few rare occurrences of events after much of the southern part of the great circle path was sunlit, but when the terminator was within ~400–1600 km to the west. Interpretation of such events would require consideration of precipitation regions at some distance from the affected great circle path. From direction finding on correlated whistlers at Palmer, *Carpenter and LaBelle* [1982] inferred

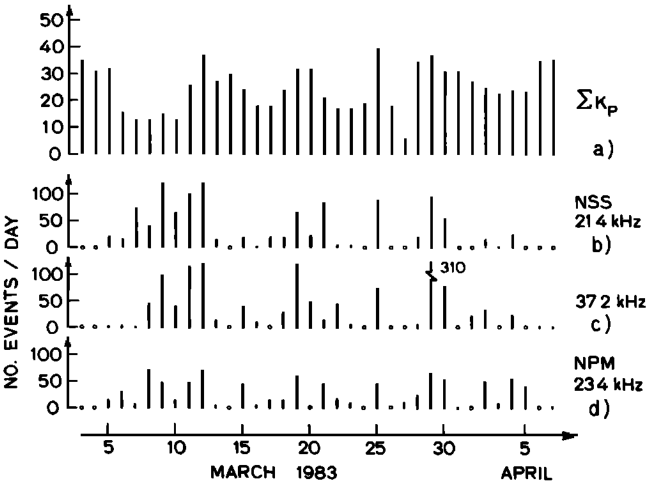

Fig. 3. Occurrence data on amplitude perturbations and magnetic activity during the March–April 1983 period of study. (*a*) Daily Σ*Kp*. (b) Daily totals of amplitude perturbations on NSS signal received at Palmer. (*c*) Same for 37.2 kHz. (*d*) Same for NPM.

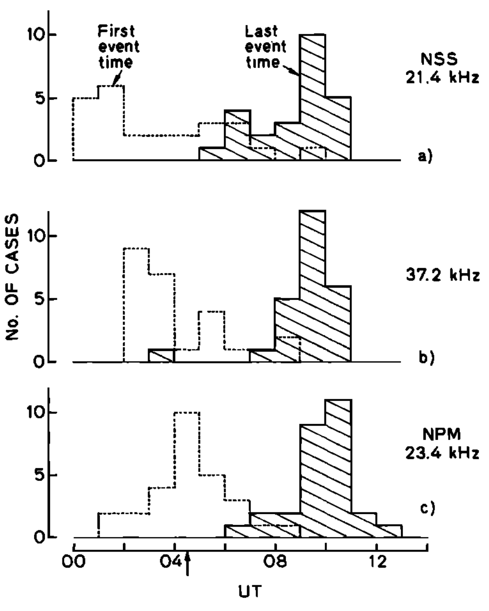

Fig. 4. Distribution of the first and last amplitude perturbations of the night during the March–April 7, 1983, period of study at Palmer. Local midnight at Palmer is indicated by an arrow. (*a*) NSS data. (*b*) 37.2 kHz. (*c*) NPM.

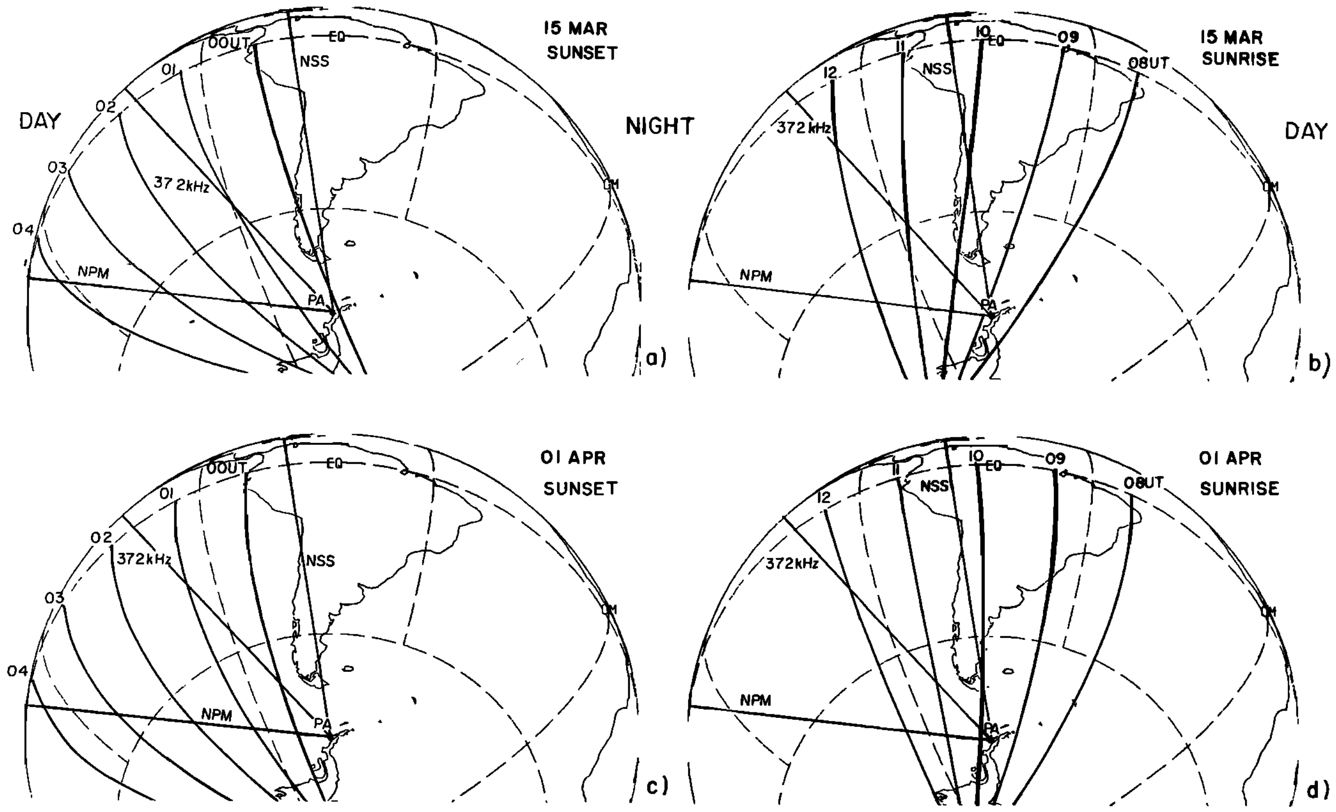

Fig. 5. The relationship of the sunset/sunrise terminator at 100 km altitude to great circle paths from several VLF/LF signal sources to Palmer. (*a*) Sunset terminator at hourly intervals on March 15. (*b*) Sunrise terminator on March 15. (*c*) Sunset terminator on April 1. (*d*) Sunrise terminator on April 1.

that in some cases the precipitation regions overlapped the affected great circle paths, but that in others they were centered up to ~200 km from the paths [*Carpenter and LaBelle*, 1982].

From the foregoing, we conclude that most of the active precipitation regions were located within a distance of ~1000 km of Palmer. This is consistent with the findings of *Carpenter and LaBelle* [1982] which were based upon the analysis of whistlers correlated with Trimpi events.

Both the 37.2-kHz and NPM signals exhibited "post-sunrise" events as their respective great circle paths became partially sunlit. On NPM such events tended to be more frequent and to occur at greater distances from Palmer. This tendency may be attributed to the higher latitude of the dark portion of the NPM path (see Figure 2) and a corresponding higher rate of ducted whistler activity [*Helliwell*, 1965]. Another contributing factor may be an increase in particle scattering efficiency with increasing *L* [*Inan et al.*, 1982].

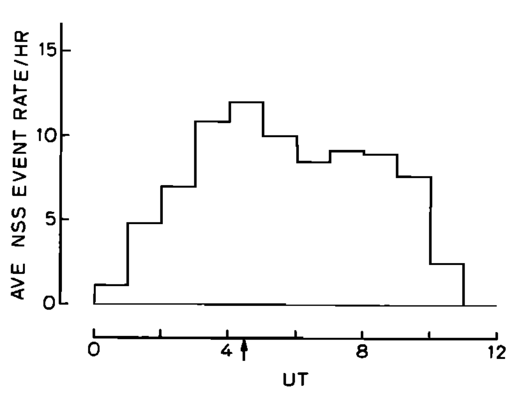

Fig. 6. Distribution of Trimpi events on NSS during the night. Local midnight over Palmer is indicated by an arrow. These are average values of the hourly event rates for the 11 nights on which more than 40 events were observed.

The data of Figures 4 and 5 suggest that darkness over an entire signal path is a favored condition for occurrence of Trimpi events. Under such conditions, modes other than the lowest order may propagate more efficiently from the source to the vicinity of the receiver. Requirement of a path under darkness appeared to be somewhat less stringent for the sources whose paths make a large angle with the terminator. For example, the NPM signal, on a sea path from the west, exhibited small events when only a limited portion of the path near Palmer was in darkness. The recognition of these events, most of which were proportionately within the ~2–10% range of those observed at higher signal levels, was facilitated by the strength (~20–80 μV/m) and stability of the signal, which benefit from the sea surface along the path and from extended propagation under a sunlit *D* region before crossing the terminator. Observation of such NPM events at essentially daytime signal levels is understandably a presunset occurrence. After sunrise, the dark portion of the path is over the transmitter, at great distance from Palmer.

While the conditions of solar illumination appear to control the earlier onsets and later terminations of Trimpi activity, other factors are clearly involved in the day-to-day temporal variations of the onsets and terminations. Our studies of the effects of the whistler rate on onset time were inconclusive. Whistler records from three nights of moderate to high Trimpi event activity were examined. In one case, March

29, 1983, whistlers and Trimpi effects were both present at relatively high rates from sunset onward. In another case, March 30, no Trimpi events and no whistlers were detected until several hours after sunset. The first Trimpi events were observed at approximately the time of the first 10-min recording containing whistlers that were identifiable on spectrograms. On this night, when the whistler rate was low, there was a nearly one-to-one correlation between whistlers and Trimpi events. On the night of March 18, 1983, the whistler rate was very high immediately after sunset, but Trimpi events were not detected for several hours. When the whistler rate decreased to 20–25 whistlers per minute, Trimpi events began to appear. In this case, however, the whistler rate was an order of magnitude greater than the Trimpi rate.

The foregoing examples underscore the complexity of the relationships between observed whistler activity and Trimpi events. Further study of these relationships is clearly needed. For example, *Carpenter and LaBelle* [1982] investigated a case involving a high whistler rate in which only a few of the whistlers were correlated with amplitude perturbations. Those few contained a particular component, not present in the others, the propagation path of which was favorably located with respect to the perturbed signal and receiving station, as indicated by direction-finding data.

Data on the distribution of Trimpi events on NSS during the course of the night are presented in Figure 6. Shown are average values of the hourly Trimpi rates for the 11 nights on which more than 40 events were observed (see Figure 3). Local midnight at Palmer is indicated by an arrow. The values increase prior to midnight and then maintain a level near ~10 events/hr until dawn. This result differs slighty from findings of a predawn peak in NSS events in October, 1963 at $L \sim 4.1$ [*Helliwell et al.*, 1973]. The results are broadly consistent with findings on whistler occurrence, which generally show relatively high rates, compared to dayside minima, for most of the night, and in some seasons and locations show a predawn peak in activity [*Laaspere et al.*, 1964].

The lack of symmetry of the distribution around midnight is not yet understood. It may be associated with a concentration of whistler activity on meridians to the west of the station, where sunset and sunrise occur at later hours.

Case studies relating whistler rates to relatively early terminations of Trimpi events have not yet been made. However, on the several days for which whistler spectra were examined, whistlers continued to be observed after the end of Trimpi activity at 'sunrise.'

5. SUMMARY

1. We confirm the earlier findings that whistler-associated perturbations of subionospherically propagating VLF/LF signals (Trimpi events) are essentially a nighttime phenomenon. Most events were observed either during conditions of nighttime signal levels or during transitions to or from nighttime levels. On a west-east sea path, to Palmer, Antarctica ($L \sim 2.4$), small events were recognizable at essentially daytime signal levels, but only near sunset, when a limited region near the receiver was in darkness.

2. Between March 3 and April 7, 1983, Trimpi events occurred near $L = 2$ on 70% of the nights. The observations were made on three VLF/LF transmitters whose great circle paths cover a range of about 90°.

3. Apparently due to the controlling influence of the sunrise/sunset terminator, the longest periods of Trimpi observations occurred on north-south signal paths that in March make small angles with the terminator.

4. Signal paths making larger angles with the terminator were used to deduce that most events occurred because of ionospheric effects within ~1000 km of Palmer Station. This finding is consistent with results from previous studies based upon other sources of information.

5. Events can be observed on a signal after sunrise over the observing station Palmer, apparently due to precipitation in dark regions as far as ~1800 km away.

6. An observed difference between two paths in the occurrence of this postsunrise continuation of Trimpi events suggests that a fall-off in Trimpi effects occurs below $L \sim 2$ because of a reduction in whistler activity and/or a reduction in particle scattering efficiency.

7. The onsets and terminations of activity observed at Palmer Station tend to concentrate near local sunrise and sunset, but also showed wide variations between those times, particularly in the case of onsets. The influence of the whistler occurrence rate and the geographic location of lightning activity on Trimpi effects are clearly important and require further study, particularly in the light of known nonuniformities in the distribution of whistler sources with respect to hemisphere and longitude [e.g. *Helliwell*, 1965; *Laaspere et al.*, 1963].

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