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SIMULTANEOUS DISTURBANCE OF CONJUGATE IONOSPHERIC REGIONS IN ASSOCIATION WITH INDIVIDUAL LIGHTNING FLASHES

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Abstract. Characteristic whistler-associated amplitude perturbations of subionospheric VLF or LF signals ("Trimpi events") observed within one second of each other at Palmer Station, Antarctica and at Arecibo, Puerto Rico suggest that ionospheric regions in both northern and southern hemispheres are disturbed together in association with individual lightning flashes. During a one hour period on March 21, 1989, the onsets of 44 out of 47 perturbations measured on a 21.4 kHz signal from Maryland to Arecibo occurred within 1 s of perturbation onsets measured on a 23.4 kHz signal from Hawaii to Palmer Station. Similar activity occurred before and after this period, and on the preceding and following days. The observations are consistent with the disturbance of geomagnetically conjugate ionospheric regions by multiple bounces between hemispheres of bursts of radiation belt electrons, scattered in pitch angle by whistlers in the magnetosphere. Analysis of patterns of perturbations with corresponding whistler and lightning information from this period suggests that there were at least two distinct ionospheric disturbances in each hemisphere.

1. VLF/LF Perturbations

During the morning of March 21, 1989, Arecibo, Puerto Rico, and Palmer Station, Antarctica recorded several hundred perturbations on signals from five VLF and LF communication transmitters in the United States (Table 1). These perturbations were characteristic of Trimpi events [*Inan and Carpenter*, 1986], having sudden (0.2 to 2 s) positive or negative onsets of up to 9 dB in amplitude followed by slow (10 to 100 s) recoveries to prior levels. Between 0900 and 1000 UT these events were particularly large and frequent on the NSS and 48.5 kHz signals at Arecibo and on the NPM signal at Palmer Station. The latter signal path was perturbed at least twice as often as any other path recorded at either site, averaging 4 perturbations per minute. Partial maps of the ten signal paths monitored are shown in Figure 1.

TABLE 1. Transmitters observed at Arecibo and at Palmer.

Call Sign	Transmitter	Frequency	Latitude	Longitude
NSS	USN Maryland	21.4 kHz	39°N	76°W
NPM	USN Hawaii	23.4 kHz	21°N	158°W
NAA	USN Maine	24.0 kHz	45°N	67°W
NLK	USN Washington	24.8 kHz	48°N	122°W
	USAF Nebraska	48.5 kHz	42°N	98°W

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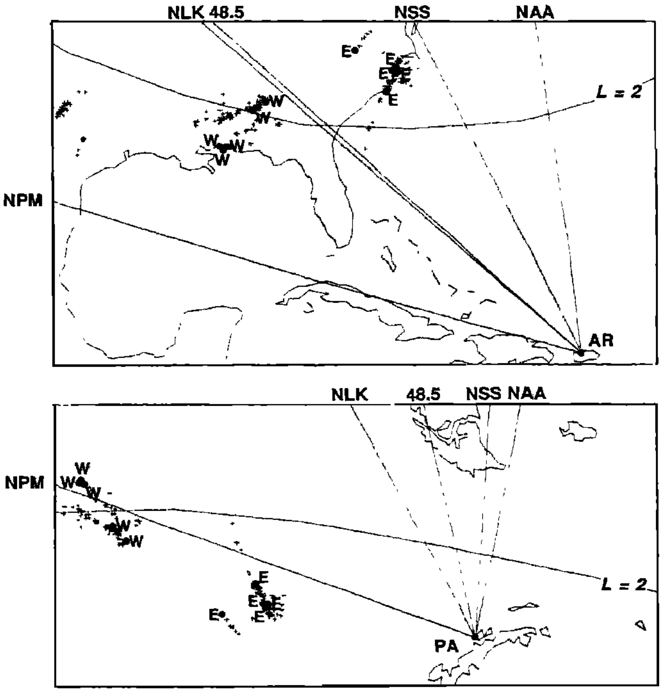

Fig. 1. Great-circle paths of subionospheric signals from the five VLF/LF communication transmitters listed in Table 1 to Arecibo, Puerto Rico (AR) and Palmer Station, Antarctica (PA). Each cloud-to-ground lightning flash recorded by the SUNY-Albany detection network between 0940 and 0950 UT on March 21, 1989 is shown by a + in the upper panel to indicate general thunderstorm activity. Each of ten additional flashes time-associated with signal perturbations discussed in the text and occurring between 0900 and 1000 UT is marked with a •. The geomagnetic conjugates of all upper panel flashes are similarly marked in the lower panel. Of the ten specially marked flashes, the five labeled 'E' were associated with perturbations of NSS but not 48.5 kHz at Arecibo, while the five labeled 'W' were associated with perturbations of 48.5 kHz but not NSS at Arecibo. All ten flashes were associated with perturbations of NPM at Palmer. The footprint at 100 km altitude of $L = 2$ is shown for reference.

For the purposes of this study, we define an "event" as a characteristic signal amplitude perturbation with a magnitude not less than 0.2 dB, and treat perturbations seen on different signals at the same or different sites as a single, simultaneously observed event when the perturbation onsets occur within one second of each other. Between 0900 and 1000 UT, 129 events were observed simultaneously at both Arecibo and Palmer. Such events accounted for 88% of the 147 events observed at Arecibo but only 51% of the 252 events observed

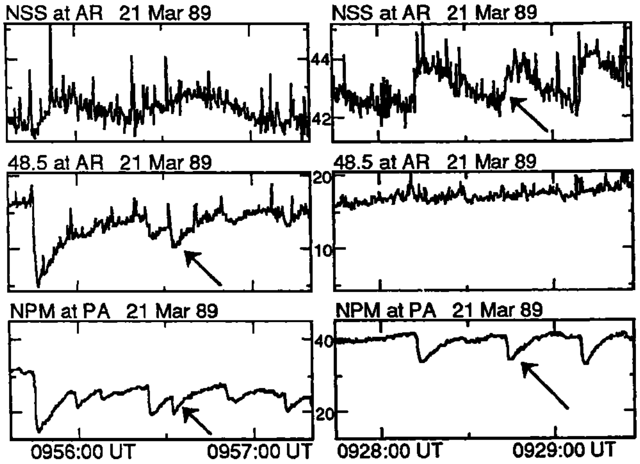

Fig. 2. Examples of simultaneously observed subionospheric signal perturbations. The left panels show perturbations of NPM at Palmer and of 48.5 kHz but not (except for one case) NSS at Arecibo, referred to as "west group" events in the text. The right panels show perturbations of NPM at Palmer and of NSS but not 48.5 kHz at Arecibo, referred to as "east group" events in the text. In both, the onsets of many of the perturbations of NPM at Palmer occur within 1 s of perturbation onsets observed at Arecibo. The arrows indicate perturbations which are shown in greater detail in Figure 4. Signal amplitudes were measured within a bandwidth of 500 Hz centered at the nominal transmitter frequency (see Table 1), time-averaged in blocks of 0.32 s, and plotted in linear units representing percent of full scale range.

at Palmer during that period, so that disturbances in the north were more likely to have counterparts in the south than vice-versa. Examples of events simultaneously observed at both sites are shown in Figure 2.

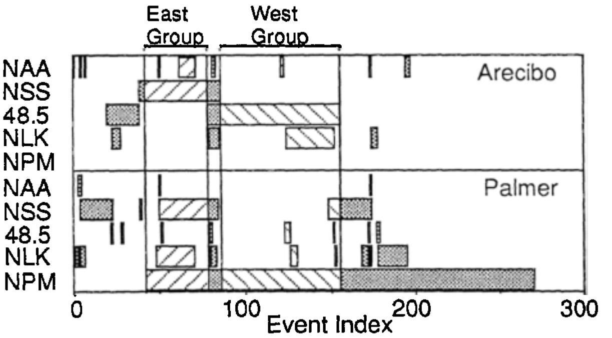

Fig. 3. Simultaneity of perturbation onsets ("events") observed on subionospheric signals from five transmitters (see Table 1), received at Arecibo and Palmer Station between 0900 and 1000 UT on March 21, 1989. Perturbation onsets observed within 1 s of each other at the same or different sites are regarded as a single, simultaneously observed event. Each of the 270 events observed during the hour is represented by a vertical column, shaded for each signal path which was perturbed in that event. Cross-hatched shading indicates events belonging to the "east group" or "west group," defined in the text. The events have been sorted for maximum contiguity of shading, so as to highlight common combinations of simultaneity; the "event index" does not in any way represent chronological order.

The graph in Figure 3 summarizes the patterns of simultaneity observed among the ten signal paths studied. At least two major groups of simultaneous events stand out: events which were observed on NPM at Palmer and NSS at Arecibo but not on 48.5 kHz at Arecibo (hereafter referred to as the "east group"), and events which were observed on NPM at Palmer and 48.5 kHz at Arecibo but not on NSS at Arecibo (hereafter referred to as the "west group"). The fact that these two groups of simultaneity exist suggests that at least two different regions of ionospheric disturbance were perturbing the signal paths observed. To investigate this possibility, the two groups were compared.

As shown graphically in Figure 3, east group events accounted for 36 and west group events accounted for 70 of the 129 events observed at both sites. Eight additional events involved both NSS and 48.5 kHz at Arecibo as well as NPM at Palmer, and are not included in either group. East group and west group events were interspersed during the hour studied, but not evenly. Most east group events occurred around 0930 UT, while most west group events occurred around 0955 UT.

Sixteen well-defined events, nine from the east group and seven from the west group, were selected to represent the two categories. These sixteen events and associated whistlers were studied in detail.

2. Associated Whistlers

The onset of each of the sixteen selected events occurred simultaneously with a whistler recorded at Palmer Station, which is consistent with similar, previously reported comparisons [*Inan and Carpenter*, 1986]. The radio atmospheric associated with each of these whistlers was identified in the Palmer broadband data with an accuracy of ±0.03 s. The time of each radio atmospheric was then corrected by 0.04 s of approximate propagation delay to Palmer Station from its conjugate point.

Figure 4 shows a high-resolution comparison of the perturbation onsets with spectrograms of the associated whistlers for the east group and west group Trimpi events marked with arrows on Figure 2. The west group whistler differs in at least two ways from the east group whistler. First, the whistlers appear to have traversed slightly different L-shells; analysis of whistler traces and corrected radio atmospherics associated with each group indicates propagation at $L = 2.1$ for the west group and at $L = 2.3$ for the east group [*Carpenter and Smith*, 1964]. Second, the west group whistler is over 10 dB less intense than the east group whistler, and the portion of the west group whistler below the earth-ionosphere waveguide cutoff at ~ 2 kHz appears to be more severely attenuated than that of the east group whistler.

Both of these differences between east group and west group whistlers were consistent among all sixteen whistlers examined. They imply the association of at least two groups of whistler ducts with the two groups of Trimpi events. The ionospheric exit regions from these two ducts appear to be in one case nearer to Palmer Station, higher in L-shell, and associated with the east group; in the other, they appear to be farther from Palmer, lower in L-shell, and associated with the west group.

Identification of the associated radio atmospheric and approximate correction for propagation delay also makes possible the determination of "onset delay," defined here as the time between the time-corrected atmospheric and the onset

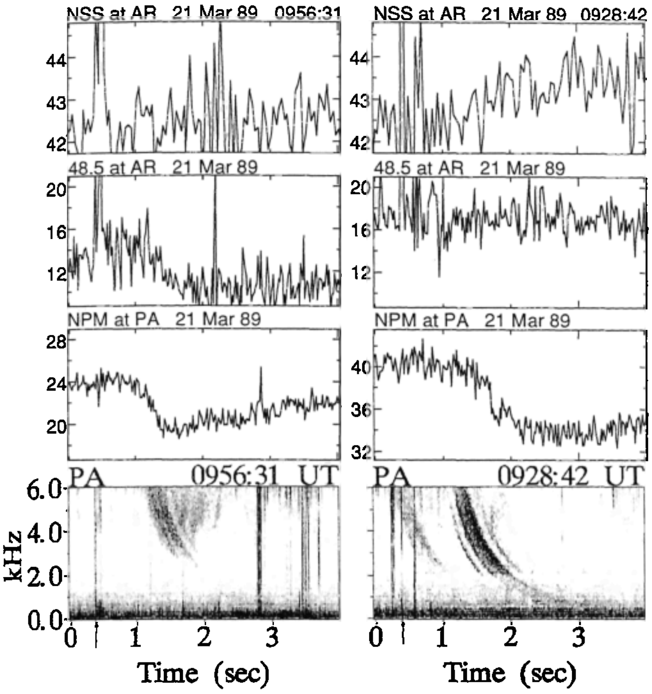

Fig. 4. Detailed comparison of whistlers recorded at Palmer with perturbation onsets observed at Arecibo and Palmer. The perturbations illustrated are marked with arrows on Figure 2, and are time-averaged in blocks of 0.04 s. On the left is a multipath whistler typical of those associated with "west group" events (see Figure 2), on the right a multipath whistler typical of those associated with "east group" events. The radio atmospherics associated with both are identified by arrows.

of an associated signal perturbation. Onset delays were measured for each perturbation involved in the sixteen events, and are compared in Figure 5. Large error ranges in some cases are due to uncertainties introduced by atmospheric and other noise. Nevertheless, it is apparent that the perturbations observed in the southern hemisphere frequently began 0.3 to 0.6 s before the corresponding perturbations observed in the northern hemisphere. It also appears that east group onset delays were in general 0.2 to 0.4 s longer than their counterparts in the west group. The greater east group delays are consistent with whistler-associated electron precipitation from a higher L-shell, where whistler propagation and electron bounce times would be longer [*Chang and Inan*, 1985].

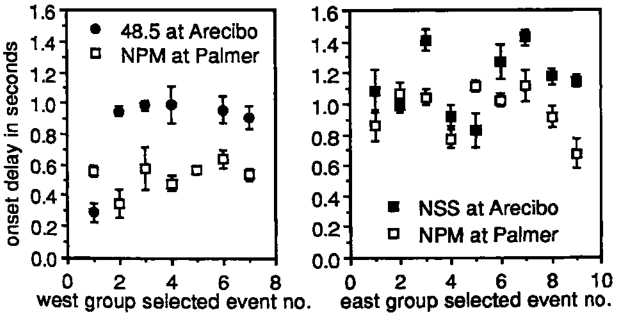

Fig. 5. Comparison of onset delays (defined in the text) measured for some of the simultaneous perturbations involved in sixteen selected events, seven from the west group and nine from the east group. The onset delay for the perturbation of 48.5 kHz in event number 5 of the west group could not be determined due to noise.

3. Lightning

Lightning time and location data from the SUNY lightning detection network [*Orville et al.*, 1987] were examined, first to locate the North American regions affected by thunderstorms during the period in question, and then to see if particular lightning flashes responsible for the sixteen analyzed whistlers could be identified in the SUNY data.

Figure 1 maps the locations and conjugates of all flashes detected by the network between 0940 and 0950 UT as a general indication of thunderstorm activity. Also mapped are ten flashes whose first strokes occurred within 0.03 s of the times, corrected for propagation delay, of radio atmospherics associated with the sixteen representative whistlers. Of these ten flashes, five correspond to the east group and five to the west group, and are labeled 'E' and 'W', respectively. Six of the ten flashes were separated in time by more than one second from other flashes recorded by the network, further decreasing the likelihood that the close time correspondence between the time-corrected radio atmospherics and the SUNY flashes is coincidental.

Of the ten flashes time-associated with the representative whistlers, the five associated with the east group all occurred in east coast thunderstorms, and the five associated with the west group all occurred in gulf coast thunderstorms. The consistency with which these flash locations correspond to the two groups of events studied suggests a correlation in this case between the location of a flash and the location of an associated ionospheric disturbance. The general significance of this correspondence is not clear; *Inan and Yip* [1989] examined recent data involving the midwestern United States with no such correlation, and concluded that any spatial relationship between lightning flashes and associated ionospheric disturbances may depend on geographic, atmospheric, and magnetospheric factors which are at present poorly understood.

4. Discussion

The possibility of conjugate precipitation associated with individual lightning flashes has been implied by recent analyses of satellite and ground-based data. *Inan et al.* [1985] showed that radiation belt electrons scattered by waves into the bounce loss cone do not necessarily precipitate in the first encounter with the atmosphere, but can backscatter and remain trapped for one or more hops before precipitating. Atmospheric backscatter can reflect up to 90% of electrons that would otherwise precipitate, as a result of the grazing angles at which wave-scattered electrons reach the atmosphere [*Berger et al.*, 1974]. Evidence presented by *Voss et al.* [1984] supported this hypothesis, showing that the lifetime of bursts of electrons scattered into or near the bounce loss cone by whistlers may be as long as four bounce periods. Such bursts would have the opportunity to disturb the ionosphere in both northern and southern hemispheres.

The measured onset delays show a tendency for the southern hemisphere to be disturbed before the northern hemisphere in simultaneously observed events. At first thought, this result is contrary to what would be expected from a southbound whistler wave inducing "direct" precipitation into the north, followed by "mirrored" precipitation into the south [*Chang and Inan*, 1985].

A difference in northern and southern electron loss cone angles could explain this behavior. At longitudes near Palmer Station, the southern hemisphere loss cone is wider than the northern hemisphere loss cone as a result of the South Atlantic magnetic anomaly. As a result, typical trapped electron flux at the edge of the southern loss cone can be 10 to 100 times larger than that at the edge of the northern loss cone [*Inan et al.*, 1988], and the first significant precipitation induced by northern hemisphere lightning may well strike the southern hemisphere after mirroring in the north. Later disturbance of the northern hemisphere could then result from precipitation of electrons which backscattered from the atmosphere in the south. Such twice-reflected precipitation is also consistent with our finding that the disturbances observed in the north were more likely to have counterparts in the south than vice-versa.

At least two groups of events were detected during the period investigated. These two groups differ in the combinations of signal paths which were perturbed, the perturbation onset delays, the characteristics of the associated whistlers, and the location of the associated lightning, implying that at least two separate ionospheric regions were disturbed in each hemisphere. This result suggests that analysis of patterns of simultaneous perturbations observed in conjugate regions may shed additional light on the size, shape, and location of ionospheric disturbances in either hemisphere.

In the southern hemisphere, both disturbed regions appear to have been near the NPM to Palmer great circle path. The relatively high rate of perturbations occurring on NPM at Palmer on this day as well as others could therefore be a result of multiple and distinct regions of ionospheric disturbance in the southern hemisphere. *Wolf* [1990] showed that the NPM signal appears to be more commonly perturbed than any other monitored at Palmer. In light of the results presented here, it is perhaps no coincidence that this signal path lies conjugate along much of its length to the southeastern United States, a region known for frequent and widespread thunderstorm activity.

The events of March 21, 1989 followed one week after the height of one of the biggest geomagnetic storms since quantitative records began in 1868 [*Allen et al.*, 1989]. This storm may have influenced the location, size, and occurrence rate of the ionospheric disturbances which were observed; still, similar conjugate disturbances were measured on April 8, three weeks after the storm peaked.

5. Summary

The disturbance of ionospheric regions in both hemispheres in association with individual lightning flashes suggests a broader role for LEP events in the coupling of lower and upper atmospheres: thunderstorms in one hemisphere can disturb the ionosphere in both. Observation of conjugate ionospheric regions may effectively double the amount of ground-based data available on individual LEP events. Future analysis of patterns of conjugate ionospheric disturbances could yield clues about their geographic distribution and about electron scattering and pitch angle distributions in the magnetosphere, and clarify the contribution of LEP to the equilibrium of the radiation belts.

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