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PCA EFFECTS ON A VLF TRANSANTARCTIC PROPAGATION PATH

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Abstract: We present a study of polar cap absorption events occurred from September 1967 to November 1974 and their effects on phase records of very low frequency (VLF) signals on NWC (Australia)–São Paulo (Brazil) propagation path, crossing the Antarctic continent. Nearly 50 PCAs from that period, of different intensities, were studied and the most relevant ones were analyzed in more detail. A good correlation between nighttime VLF signal phase advances and total proton flux content of energy 10 MeV<E<30 MeV measured by satellites (Explorer 34 and 41, NOAA 2 and 3 and ATS-1) was obtained for strong PCA events. Geomagnetic storms with sudden commencement, associated or not with proton precipitation, also produces well defined VLF signal phase advances. Comparison of these results with those obtained in the northern hemisphere during PCA events may provide relevant information on the behavior of the ionospheric *D*-layer over the Antarctic region. Simultaneous analysis of VLF on non-polar propagation paths were also included for the major PCA discussed. Well defined phase deviations were detected showing the significant contribution of the South Atlantic Geomagnetic Anomaly to the ionization of the lower part of the ionospheric *D*-region.

1. Introduction

Polar Cap Absorption is the term applied to the intense absorption of radio waves of certain frequencies. It is observed in high geomagnetic latitudes when the ionosphere becomes intensely ionized as a result of the arrival of energetic charged particles originating from the Sun. The particles responsible for the observed absorption are for the most part protons in the energy range from roughly 5 to 300 MeV (BAILEY, 1964). These particles precipitate in the polar regions causing an excess of ionization in altitudes corresponding to the ionospheric *D*-region, or below it.

This work analyses experimentally about 50 PCAs observed as long-enduring phase advances in very low frequency signal propagating from NWC (Australia) to São Paulo, SP (Brazil), from September 1967 to November 1974, and simultaneous phase advances observed in non-polar propagation paths during selected events that allows one to estimate comparatively the effective contribution of the *D*-region ionization due to particle trapped in the region of the South Atlantic Geomagnetic Anomaly (SAGA).

Following the PCA model proposed by HAKURA (1967), a typical PCA develops starting from an optical flare often of importance 2B or greater, is accompanied by an

X-ray burst and by a type IV radio burst. The X-ray emission produces the effect known as SID (Sudden Ionospheric Disturbance) and is identified in a VLF record as a SPA (Sudden Phase Anomaly) that occurs in the sunlight portion of the propagation path. It is assumed that all the energetic particles (electrons, protons, alpha particles and heavier nuclei) are produced simultaneously in the explosive phase of the optical flare and that all particles are in the same rigidity range (what makes them to propagate with different velocities). Satellite measurements reported by LIN and ANDERSON (1967) showed that electrons in great quantity are the first to reach the Earth (from 30 min to one hour after the flare onset), precipitating near the geomagnetic pole at a geomagnetic latitude of approximately 80°. Later on (roughly one hour) it is noticed that arrival of protons, the major component of energetic particles flux, and the PCA effect spreads out to geomagnetic latitudes below 65°. Some hours later take place alpha particles and heavier nuclei precipitation extending the affected area to 60° (FICHTEL and MCDONALD, 1967). The shock wave produced by the solar explosion travels at a velocity ranging from 500 to 1000 km/s and reaches the vicinity of the Earth 1.5 to 3 days later, causing the magnetic storm that reduces the cutoff latitudes and sometimes makes the PCA to spread out to latitudes as low as 50° (WESTERLUND *et al.,* 1969).

Satellite measurements also show that the particle flux is roughly isotropic in the whole polar region (WILLIAMS and BOSTROM, 1967; KRIMIGIS and VAN ALLEN, 1967). There is a marked anisotropy in particles arrival directions which remains only in the initial phase of PCA. The degree of anisotropy depends on the position of the flare in the solar disk because after OBAYASHI (1964), the time versus particle intensities profile depends on heliographic longitude. This is due to Sun's rotation responsible for the spiral structure of the solar magnetic field lines into the interplanetary space.

2. Propagation Path and Frequencies

The long distance propagation path NWC–SP is a peculiar one. It is a transantarctic path propagating completely over sea water from December to May and partially (4500 km) over the Antarctic ice cap from June to November. Figure 1 shows the propagation path on a polar projection, the geographic and geomagnetic poles and the contour of maximum accumulated ice on the Antarctic continent, that occurs in September. The highest geomagnetic latitude reached by the propagation path is about 70°S (geographic: 66°S).

In the initial period of data acquisition (from September 1967 to September 1968), the transmitter operated in three different frequencies (15.5, 19.8 and 22.3 kHz) weekly alternated. From April 1968 to September 1968 the frequency of 19.8 kHz was replaced by 18.0 kHz. From October 1968 onwards the transmission frequency was maintained at 22.3 kHz. The events that occurred in the initial period were submitted only to a qualitative analysis, because of the lack of continuity of data acquisition in a single frequency.

Figure 2 shows the geometry of VLF propagation paths including the 0.3 G contour of constant B at 100 km altitude given by ROEDERER *et al.* (1965). Excluding the NWC–SP propagation path, the remaining ones are all transequatorial, mid-latitude,

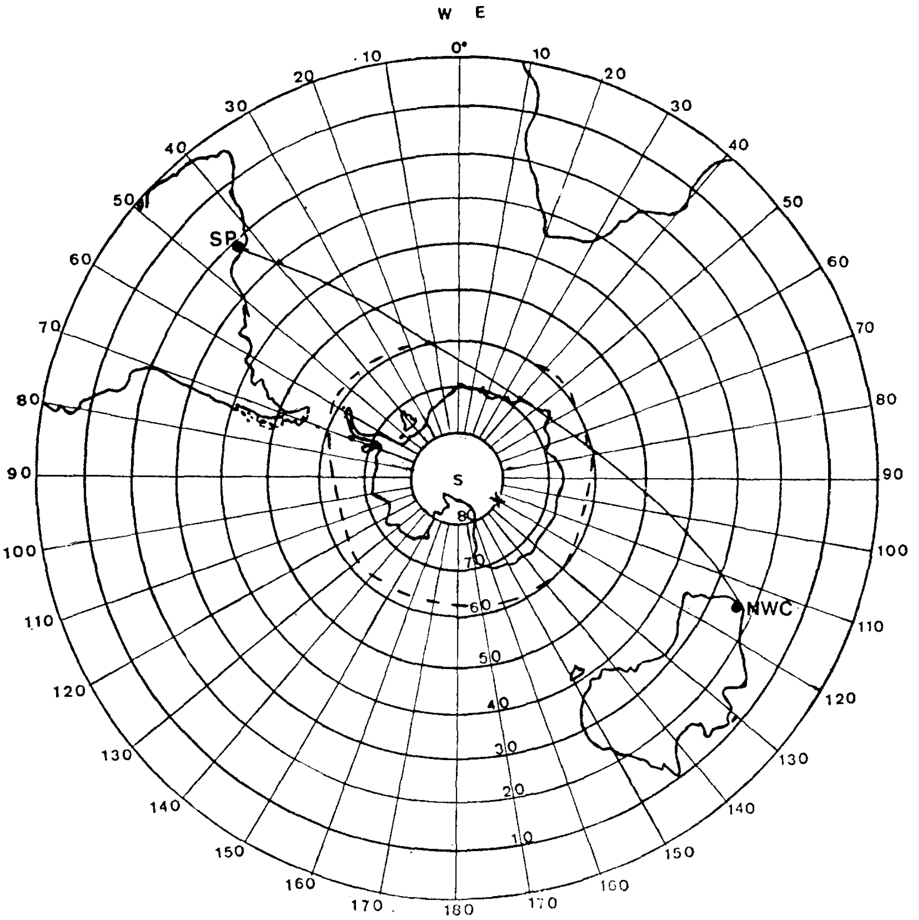

Fig. 1. Polar projection of NWC–SP propagation path. The dashed contour represents the average extent of the ice cap in September (maximum). S and X indicate the geographic and geomagnetic south poles, respectively.

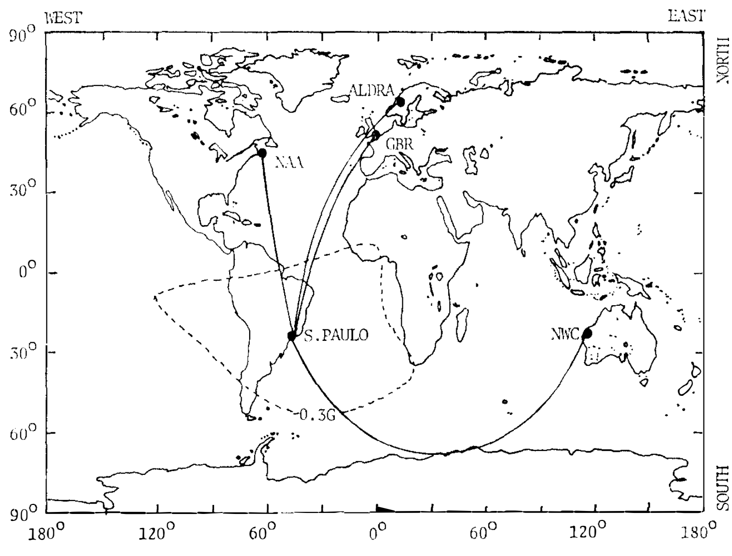

Fig. 2. Gnomonic projection of all VLF propagation paths studied. Dashed line represents the 0.3 G contour of constant magnetic field at an altitude of 100 km.

Table 1. Characteristics of monitored VLF transmitters.

Transmitter call sign	Location	Geographic coordinates	Frequency (kHz)	Total distance (Mm)	Distance inside the SAGA (Mm)
NWC	North West Cape (Australia)	21°49′S 114°10′E	22.3 (15.5)	14.6	3.0
GBR	Rugby (U.K.)	52°22′N 1°11′W	16.0	9.5	3.0
NAA	Cutler, Maine (USA)	44°39′N 67°12′W	17.8	7.9	2.7
ALDRA	South of Bodø (Norway)	66°25′N 13°9′E	12.3	11.3	2.8
Receiver site					
Umuarama Observatory S. Paulo (Brazil) (until August 1970)		22°48′S 45°30′W			
Itapetinga Radio Observatory S. Paulo (Brazil) (after August 1970)		23°11′S 46°33′W			

non-polar and cross to some extent the SAGA. Table 1 summarizes the characteristics of VLF propagation paths analyzed.

3. Description of the Events

The events were selected based on PCA effects reported by Hakura (1967), Reder (1968–1974) and Piggott and Hurst (1976). Among the selected events, following the criterion adopted by Piggott and Hurst (1976), about 10 of them considered as weak, very weak or event doubtful did not show any remarkable effect on VLF data and were neglected. Another 10, although of medium importance occurred in the period of variable transmission frequency or during the months of June to October, when the quality of data is questionable because of the increase in signal attenuation due to the low conductivity of ice (Westerlund and Reder, 1973) and also, signal propagation is deeply affected by modal conversion (Westerlund and Svennesson, 1971).

Table 2 shows the analyzed events, observed on NWC–SP propagation path together with associated optical flare, proton counting rates for proton energies greater than 10 MeV and phase advances observed in VLF signals. Column labeled by ΔH(70 km, D=3.6 Mm) presents the variation in the reflection height of the earth-ionosphere waveguide calculated after Wait (1959) for a reference height of 70 km and considering the distance D (3.6 Mm), the extension of propagation path of which after Westerlund *et al.* (1969) (for the northern hemisphere) lies beyond the geomagnetic latitude of 62.5°S, considered as the normal boundary for PCA development. Last column shows the same calculations but using as reference height 60 km and the propagation path affected was extended to 6.6 Mm because the distance of path that propagates inside the SAGA was included (see Table 1).

This PCA analysis was complemented with data of proton fluxes measured by satellites (Explorer 34 and 41, NOAA 2 and 3, ATS-1), optical flares, geomagnetic

Table 2. PCA effects and its association with optical flares, geomagnetic indices, proton flux and ionospheric D region lowering.

PCA			Flare data		Ap index	J (Ep>10 MeV) particles/cm^2·s·sr	ΔH, 70 km D=3.6 Mm	ΔH, 60 km D=6.6 Mm
Date	$\Delta\phi$ (μs)	Type	Observed UT	Importance				
13 Oct 67	7 (14 Oct)	D	not identified		13 (14 Oct)	—	4.3	2.4
2 Nov 67	6 (3 Oct)	D	2 Nov 0855	2B	23 (3 Nov)	—	3.7	2.1
15 Feb 68	13 (18 Feb)	D	not identified		35 (20 Feb)	—	8.1	4.5
28 Mar 68	8 (29 Mar)	D	not identified		27 (30 Mar)	—	5.0	2.8
31 Mar 68	12 (2 Apr)	D	not identified		27 (1 Apr)	—	7.5	4.2
*4 Apr 68	7 (8 Apr)	D	not identified		36 (6 Apr)	—	3.9	1.2
*9 June 68	32 (11 June)	A	9 June 0835	2B	103 (11 June)	354 (10 June)	24.0	11.1
*9 July 68	15 (14 July)	A	9 July 1805	2B	35 (10 July)	54 (13 July)	8.5	3.6
26 July 68	7 (27 July)	D	not identified		15 (26 July)	—	4.3	2.4
29–31 Oct 68	21 (29 Oct)	A	20 Oct 1115	2B	122 (1 Nov)	1200 (31 Oct)	13.1	7.3
18 Nov 68	44 (18 Nov)	B	18 Nov 1026	1B	22 (18 Nov)	849 (18 Nov)	33.0	15.9
4 Dec 68	19 (6 Dec)	A	2 Dec 2027	3N	25 (5 Dec)	152 (6 Dec)	11.8	6.6
24 Jan 69	5 (24 Jan)	C	24 Jan 0707	2N	29 (25 Jan)	6 (24 Jan)	3.1	1.7
25 Feb 69	25 (25 Feb)	B	23 Feb 0500	1B	32 (27 Feb)	25 (25 Feb)	15.6	8.7
			24 Feb 2330	2B				
			25 Feb 0928	2B				
16 Mar 69	7 (17 Mar)	D	12 Mar 1744	1B	38 (17 Mar)	—	4.3	2.4
21–27 Mar 69	25 (23 Mar)	C	21 Mar 0142	2B	79 (24 Mar)	5 (22 Mar)	15.6	8.7
29–31 Mar 69	30 (31 Mar)	C	30 Mar 0248	2B	24 (1 Apr)	66 (31 Mar)	18.7	10.4
5 Nov 70	11 (7 Nov)	B	5 Nov 0312	3B	58 (7 Nov)	42 (4 Nov)	6.8	3.8
23 Nov 70	8 (23 Nov)	D	not identified		30 (21 Nov)	1 (23 Nov)	5.0	2.8
24 Dec 70	13 (26 Dec)	C	not identified		14 (24 Dec)	5 (24 Dec)	8.1	4.5
8 June 72	12 (10 June)	C	8 June 1357	-F	14 (9 June)	10 (9 June)	7.5	4.2
16 June 72	23 (18 June)	C	not identified		126 (18 June)	21 (17 June)	14.3	8.0
19 June 72	28 (22 July)	C	not identified		33 (25 July)	25 (20 July)	17.4	9.7
4 Aug 72	58.5 (4 Aug)	A	2 Aug 0310	1B	132 (4 Aug)	68486 (4 Aug)	43.7	20.3
			2 Aug 1959	2B	182 (5 Aug)	13740 (8 Aug)		
			4 Aug 0619	3B				
			7 Aug 0348	1B				
			7 Aug 1505	3B				
3 July 74	33 (5 July)	B	3 July 0833	-B	130 (6 July)	300 (5 July)	20.6	11.5

A=Strong, B=Medium, C=Weak, D=Very weak, *frequency 15.5 kHz.

indices *Kp* and *Ap*, magnetic storms, ionosonde, riometer, and other VLF effects supplied by Solar Geophysical Data Bulletins (NOAA, 1968, 1969, 1972, 1973, 1974).

Among the events analyzed, the most relevant ones were selected and are described in detail.

3.1. PCA of 18 November 1968

This event originated after a type 1B optical flare that occurred at 1026 UT on November 18. A magnetic planetary index of 22 was observed on November 18 and three strong magnetic storms occurred: one on November 16 at 0916 UT, on November 20 at 0905 UT and on November 24 at 1558 UT.

A peak proton flux of 849 particles/cm^2•s•sr of energy greater than 10 MeV was measured by Explorer 34 at 1400 UT on November 18 recovering to background level on November 26. A second sharp peak occurred on November 24 at 0500 UT. Pioneer 9 ($E > 13.9$ MeV) indicated largest value (3.5 orders of magnitude above background) at 2346 UT on November 23.

A maximum phase advance in VLF signal of 44.0 μs was observed on November 18 around 2200 UT. There are evidences of phase advances also following the two magnetic storms reported above. The superposition of the two effects does not allow a precise evaluation of phase deviation produced by field perturbation. VLF signal recovered to normal quiet phase pattern on November 26. Plots of nighttime phase advances versus proton flux of energy greater than 10 MeV showed a better correlation than that of daytime phase advances. Figure 3 shows the observed phase advance compared to (a) normal phase pattern and (b) corresponding proton flux measured by satellite for this event.

Simultaneous analysis of ALDRA (Norway)–SP (Brazil) propagation path showed a maximum phase advance of 28.0 μs on November 19, corresponding to a $\Delta H = 15.9$ km. The two first magnetic storms would be responsible for such lowering of the reference height in the Anomaly region, once an additional lowering of 6.3 km occurred on NWC-SP propagation path on November 25, probably caused by the last magnetic storm (November 24).

3.2. PCA of 4 August 1972

This event is considered as a sequence of several consecutive effects. A first proton peak flux with 68486 particles/cm^2•s•sr detected by Explorer 41 occurred at 2200 UT on August 4, a second one occurred at 0500 UT on August 8 with maximum of 13740 particles/cm^2•s•sr. ATS-1 satellite detected a proton peak flux of 6633 particles/cm^2•s for proton energies of 5–21 MeV at 1900 UT on August 5. Five optical flares were responsible for this major event: August 2 at 0310 UT of importance 1B, August 2 at 1959 UT of importance 2B, August 4 at 0619 UT of importance 3B, August 7 at 0348 UT of importance 1B and August 7 at 1505 UT of importance 3B. Five strong magnetic storms were also reported in this period: on August 4 at 0119, 0220 and 2054 UT, on August 8 at 2354 and on August 9 at 0037 UT. Planetary index *Ap* was 182 on August 5, the highest value observed in 1972.

VLF phase advances were observed in NAA (USA)–Inubo (Japan) (17.8 kHz), GBR (England)–Inubo (Japan) (16.0 kHz) and NPG (USA)–Inubo (Japan) (18.6 kHz) propagation paths with maximum deviation of 65.0 μs (on August 4 at 2100 UT),

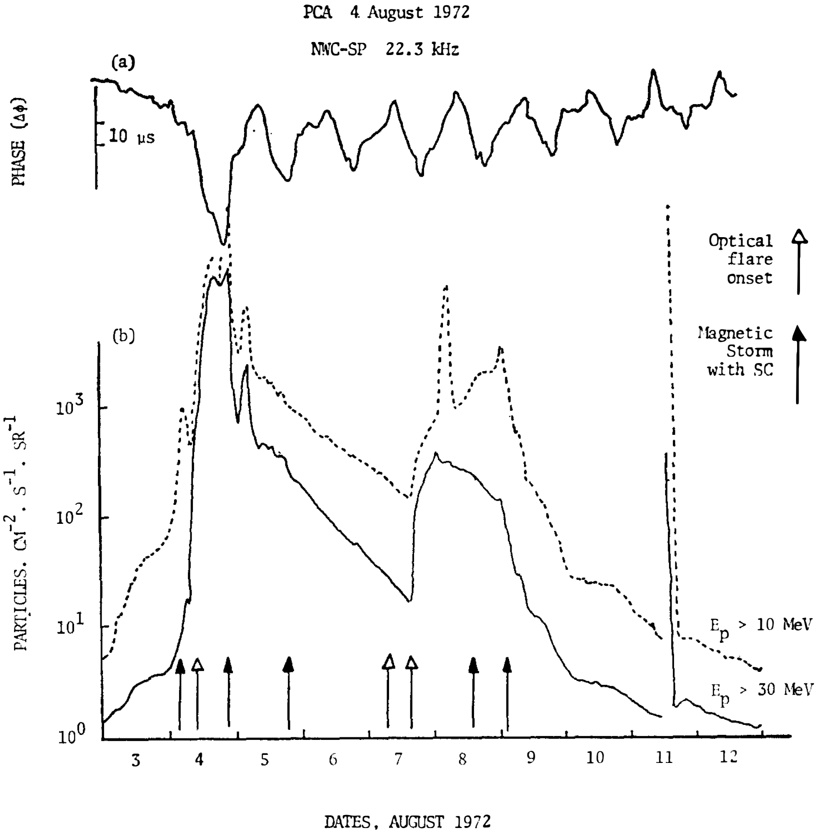

Fig. 3. (a) Hourly values of VLF phase advances compared with average quiet-day curve. (b) Corresponding proton fluxes measured by satellite for energies greater than 10 and 30 MeV, for the PCA event of 18 November 1968.

59.0 μs (on August 4 at 1430 UT) and 18.0 μs (on August 4 at 1200 UT) respectively (Hakura *et al.*, 1973).

The maximum phase advance on NWC–SP was 58.5 μs on August 4 coincident within one hour with peak proton flux of energy greater than 10 MeV. Daytime phase came back to normal average values on August 11 but nighttime phase reached the normal value only on August 15. The correlation between log of nighttime phase in micro-seconds versus log of proton flux of energy $E > 10$ MeV is approximately 98% while the correlation coefficient for higher energy ranges ($E > 30$ and $E > 60$ MeV) were not so good. Based on such a good correlation it was assumed that nighttime phase values recovered to normal on August 15. Figure 4 illustrates the observed phase deviation compared to (a) quiet days phase pattern and (b) corresponding proton flux measured by a satellite for this PCA.

The second proton peak of lower intensity did not produce any lowering in the ionosphere, that allows us to suppose that the saturation level has been attained earlier, during the arrival of the first higher energy proton precipitation.

On NAA–SP propagation path a phase advance of 13.0 μs was recorded on August 7 and during the following days a constant phase advance of 5.0 μs was maintained until August 19 when it recovered to its normal average value.

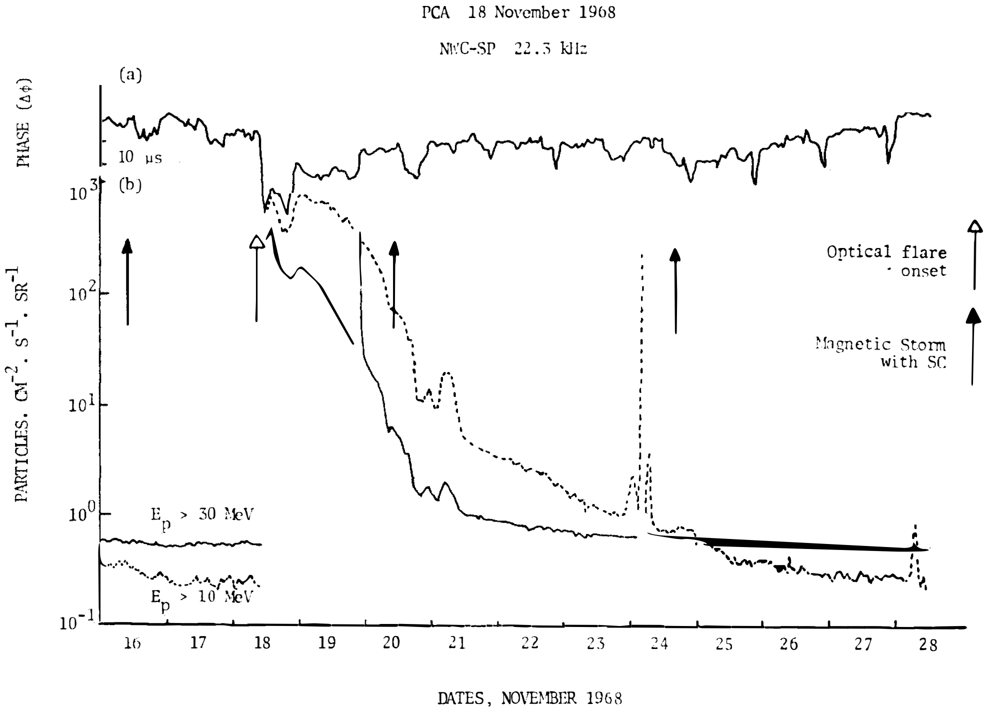

Fig. 4. (a) Hourly values of VLF phase advances compared with average quiet-day curve. (b) Corresponding proton fluxes measured by satellite for energies greater than 10 and 30 MeV, for the PCA event of 4 August 1972.

3.3. *PCA of 9 June 1968*

This PCA, associated with the 2B optical flare that occurred at 0835 UT, was one of the few analyzed in the period from September 1976 to September 1968 in the frequency of 15.5 kHz. Despite its occurrence in an unfavorable month (June), a maximum phase advance of 32 μs was observed on June 11, in VLF signals. This was a large type PCA with a maximum absorption of 5.7 dB measured by 30 MHz ionosonde (Piggott and Hurst, 1976). Although the period of observation at 15.5 kHz did not permit us to determine when signal recovered to the normal level, the analysis of subsequent data in the frequency of 22.3 kHz shows phase stability from June 14 onwards, which suggests that the recovery of signal phase occurred on June 12 or 13, in accordance to riometer data.

Proton counting of energy $E > 10$ MeV measured by Explorer 34 started at 1100 UT (June 9) with a maximum of 354 particles/cm^2•s•sr at 0600 UT (June 10) returning to the background level at 1000 UT (June 12). The magnetic activity was high, with an SSC on June 10 and the average planetary index *Ap* indicated the highest value of the year (103) on June 11.

The reflection height variation calculated for a normalized path of 3.6 Mm resulted in a $\Delta H = 24.0$ km, a value excessively high for the measured proton flux (Reder, 1981). To explain such a high ΔH, three hypothesis were admitted: a) This frequency has a reference reflection height lower than that for 22.3 kHz (Reder, 1981; Paes Leme, 1985). Calculations made using a reference reflection height of 60 km as suggested by Larsen (1971) instead of 70 km (adopted as reference) result in a $\Delta H = 20.3$ km. b)

The PCA development could spread out to lower latitudes, depending on the energy and type of incident particles. Calculations made using a path length of 6.6 Mm, admitting a superposition of two effects, one along the polar region (3.6 Mm) and another across the SAGA (3.0 Mm) would result in a $\Delta H = 13.0$ km. c) Both regions are very sensitive to field perturbations, a consequence of the high planetary index observed during this event.

A phase advance of 6.0 μs, measured on NAA (USA)–SP (Brazil) propagation path, considering as the affected region that given in column 6 of Table 1, produced a lowering of the reflection height of 5.1 km on June 12.

Assuming an isotropic distribution of ionization inside the Anomaly, we can immediately distinguish a lowering of the reflection height of 24.2 km in the anomaly region (normalized to NAA–SP propagation path) and a corresponding lowering of about 19.1 km along the polar region for the NWC–SP propagation path. This value, compared to that calculated above ($\Delta H = 13.0$ km) shows that this PCA spread out to latitudes lower than 62.5°S.

3.4. PCA of 9 July 1968

An event considered by Piggott and Hurst (1976) as very strong occurred after an optical flare type 2B at 1805 UT on July 9. Proton countings detected by Explorer 34 started on July 7 at 0100 UT with maximum of 54 particles/cm^2•s•sr ($E > 10$ MeV) on July 13 at 2200 UT recovering to background values on July 17 at 1900 UT. Two magnetic storms of SC occurred: one on July 9 at $\sim$2155 UT and another on July 13 at 1612 UT. VLF phase advance of 15.0 μs was observed on July 14. Recovery to normal quiet-day curve is uncertain because of frequency change. Magnetic planetary index Ap was 35 on July 10, the highest of the month and Kp index indicated 5^+ on July 10.

The phase advance on NAA–SP propagation path reached a maximum of 12.0 μs on July 15, that gives a lowering in the diurnal reflection height of 8.3 km, restricted to the Anomaly region. In this case, the proton flux measured by a satellite was less intense but the occurrence of the two magnetic storms probably caused this lowering on July 15, later than the maximum phase deviation observed on NWC–SP on July 14.

3.5. PCA of 4 December 1968

The optical flare of importance 3N that occurred on December 2 at 2027 UT was responsible for the PCA reported by Piggott and Hurst (1976) as a strong one. A gradual enhancement of proton counting was detected by satellite (Explorer 34) starting at 1000 UT on December 3 with peak value of 152 particles/cm^2•s•sr at 0400 UT on December 6 recovering to background level on December 13. Magnetic planetary index Ap was 25 on December 5 with a strong magnetic storm ($H = 1150\gamma$) reported on December 3 at 0400 UT and another one on December 5 at 0633 UT.

Maximum phase advance in VLF signal of 19.0 μs occurred on December 6, with recovery to average value observed on December 12, following very closely the proton flux distribution of energy greater than 10 MeV.

During this period, measurements of phase advances on ALDRA–SP propagation path showed a maximum phase deviation of 10.0 μs on December 4, ($\Delta H = 5.7$ km) one day after the occurrence of the strongest magnetic storm.

3.6. PCA of 25 February 1969

A proton event labelled by Reder (1968–1974) as medium with ground level effects. Associated flares occurred on February 23 at 0500 UT (of importance 1B), on February 24 at 2330 UT (of importance 2B) and on February 25 at 0928 UT (of importance 2B). Magnetic planetary index *Ap* was 32 on February 27 and magnetic activity (*Kp* index) was less than 3 until February 25. On February 21 an SC started at 0158 UT. A weak proton flux with a maximum of 25 particles/cm^2•s•sr of $E>10$ MeV measured by Explorer 34 at 1200 UT on February 25, was too low to produce such maximum phase advance (25.0 μs) observed in VLF signal propagation on February 25.

Phase data recorded in this period on NAA–SP propagation path showed a maximum phase advance of 10.0 μs on February 27 corresponding to a $\Delta H=9.0$ km.

3.7. PCA of 3 July 1974

An optical flare occurred at 0833 UT on July 3, of importance-B. Four magnetic storms followed this flare in the period from 4 to 8 July: July 4 at 0100 UT and at 1533 UT, on July 5 at 1931 UT, on July 6 at 0320 UT. Magnetic planetary index *Ap* showed a maximum of 130 on July 6. NOAA 2/NOAA 3 detectors attained maximum flux levels of about 300 particles/cm^2•s•sr at 1800 UT on July 5 for energy $E>10$ MeV, and about 20 particles/cm^2•s•sr for energy $E>30$ MeV. At 0000 UT on July 8 NOAA 2/NOAA 3 detectors for energy greater than 10 MeV were at background. Thule 30 MHz riometer recorded a first maximum attenuation of 1.8 dB at 2300 UT (July 3) and a second maximum of 4.6 dB at 2100 UT and 2315 UT (July 5).

Maximum daytime phase advance of 15.5 μs was observed at 1000 UT and maximum nighttime phase advance of 29.5 μs occurred at 2100 UT on July 5. Maximum phase advance of 33.0 μs occurred at 1700 UT on July 5. VLF propagation paths GBR (England)–Thule (Norway) and NLK (USA)–Thule (Norway) showed a maximum phase advance of about 40 μs and 20 μs respectively on July 5.

Simultaneous signals received from GBR during this period were useless because of lots of interruptions which make the analysis difficult.

4. Data Analysis

From a general point of view, it is possible to separate the analyzed events in two types: the fast ones which have their maximum phase advance until 12 hours after the onset of proton arrival and the slow ones which show a maximum phase advance a few days after the first proton detection by satellite. Both types are well correlated with the temporal evolution in the proton flux distribution detected by satellite for energies greater than 10 MeV. According to Westerlund *et al.* (1969), the immediate particle precipitation on the Earth is related to the flare position on the Sun's disk, being the most favorable position approximately 60° of Sun's central meridian when the magnetic field lines link the flare directly to the Earth; under these conditions are observed the fast effect events.

In the majority of the analyzed events it was possible to identify the associated optical flare. In some cases, however, the identification of the associated flare was doubtful because the delay between the flare onset and the PCA onset is very long, or because the PCA onset is not clearly defined, or else because the flare occurred on the back side of the Sun (Burlaga, 1967).

The analysis of the events showed that PCAs considered as very weak present a maximum phase deviation ranging from 6–13 μs and no proton fluxes were detected by a satellite for energies greater than 10 MeV. This leads us to suppose that these deviations are produced by the incidence of particles with energy lower than 10 MeV. After Westerlund *et al.* (1969), protons with energies greater than 7 MeV penetrates in ionospheric daytime altitudes of 70 km. In nighttime altitudes of 90 km are present protons of energy above 1 MeV. Ishii *et al.* (1973) reported that PCA events with maximum flux greater than or equal to 0.7 particles/cm^2•s•sr, for energy greater than 10 MeV, produce considerable phase anomalies on VLF propagation.

It is also possible that the phase advances observed during weak PCAs were related to magnetic activity, once in all examples the planetary magnetic index Ap was reasonably high. This is in agreement with the proposition given by Westerlund *et al.* (1969) that the magnetic activity is a remarkable factor in modulating particle flux whose effects are more sensitive for lower flux intensities.

In general, the events considered as weak or very weak that showed well defined phase advances occurred in the period from November to April, when the ice cap is reduced to the Antarctic Continent. In the period from May to October when the ice cap reaches its maximum extent, only the events classified as strong or medium show phase advances clearly defined, as can be seen from observation of Table 2.

For the event of 4 August 1972, the calculated variation in reflection height ($\Delta H=$ 43.7 km) was extremely high, even if we take into account the excessively high counting of protons detected by satellite. Following Westerlund *et al.* (1969), above a certain number of particles/cm^2•s•sr that should produce a lowering in the reflection height of about 10 km, less sensitive is the phase variation to enhancements in particles flux. Hakura *et al.* (1972), analyzing the effect of this event along the propagation path GBR (England)–Inubo (Japan) observed a lowering in the reflection height of 23.0 km, showing a good agreement with other analyzed events where the ionization responsible for the PCA is concentrated mainly in altitudes ranging from 45 to 75 km approximately (Bailey, 1964).

Figure 5 shows diurnal phase deviations from quiet day curves for the majority of PCA events analyzed. Uncertainties in the phase calculation was about 2.0 μs.

The well defined and persisting phase advances, observed on non-polar paths crossing the SAGA during the PCA events analyzed, seems to point to strong enhancement in the ionization in the Anomaly during these events (Mendes *et al.*, 1970). It is fairly well known that the mirroring height for trapped electrons in the inner radiation belt zone dips low in the atmosphere in the vicinity of the SAGA and the particles are lost through interactions with atmospheric constituents.

Table 3 resumes the effects produced during these selected PCA events described in Section 3 on non-polar VLF propagation path, that crosses the SAGA to some extent. The third column indicates the maximum daytime phase deviation observed and the last one shows the lowering in the reflection height of the earth-ionosphere waveguide for VLF signals calculated using a reference height of 60 km that is more representative for high latitude propagation paths according to Larsen (1971).

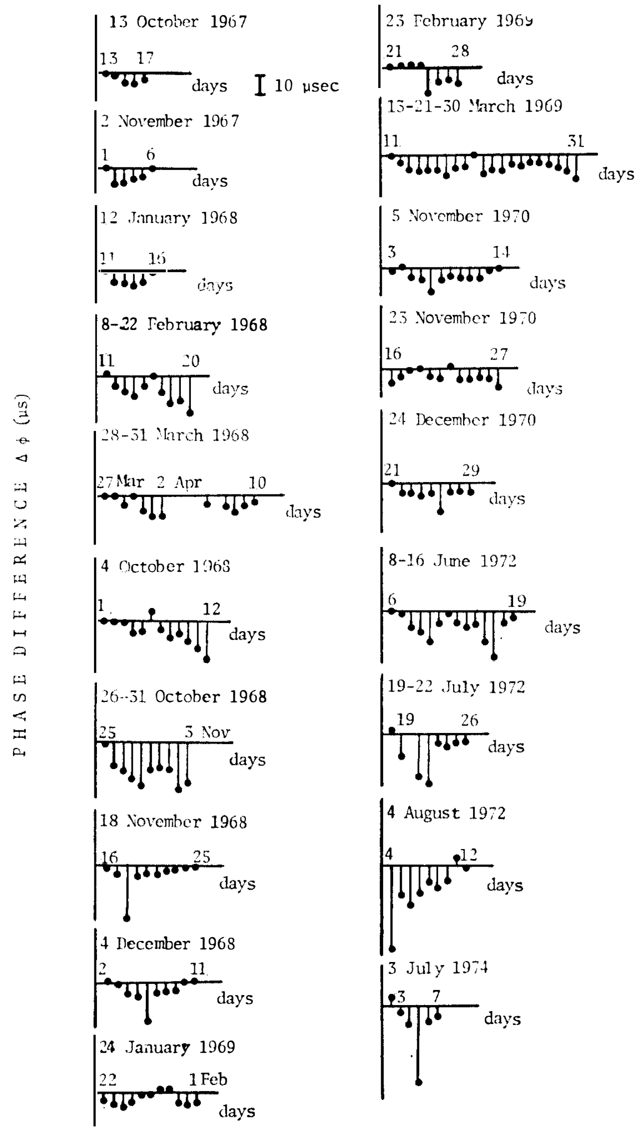

Fig. 5. Representation of some diurnal phase deviations listed in Table 2.

For NWC–SP propagation path calculations of ΔH were carried out considering an affected distance of 6.6 Mm, assuming that two regions were responsible for the observed effect: one due to the polar region limited to a maximum geomagnetic latitude of 62.5° (WESTERLUND *et al.*, 1969) defining a path length of 3.6 Mm and another due to the presence of the SAGA which limits the affected path to 3.0 Mm (inside the 0.3 G profile of constant total magnetic field).

Figure 6 shows daytime phase advances compared to quiet day curves observed on non-polar propagation paths crossing the SAGA. Remarkable lowerings in the reflection height of the lower ionospheric *D*-region are observed for the events discussed in Section 3 which values (ΔH) are given in Table 3. Other relevant cases were included to emphasize the effect of the SAGA on VLF signals propagation.

Table 3. PCA effects observed on non-polar VLF propagation paths crossing the SAGA.

Event	Transmitter	$\Delta\phi$ (μs)	ΔH (70 km)	ΔH (60 km)
9 June 68	NAA	6.0	5.1	4.2
9 July 68	NAA	12.0	8.3	7.4
18 Nov 68	ALDRA	28.0	15.9	11.8
4 Dec 68	ALDRA	10.0	5.7	4.3
25 Feb 69	NAA	10.0	9.0	7.3
4 Aug 72	NAA	13.0	6.8	5.5
27 July 69	NAA	11.0	9.4	7.6
14 Mar 70	NAA	17.0	14.4	11.7
29 Mar 70	GBR	9.0	6.3	5.0
10 July 70	GBR	14.0	9.8	6.1
7 Nov 70	GBR	6.0	4.2	3.3

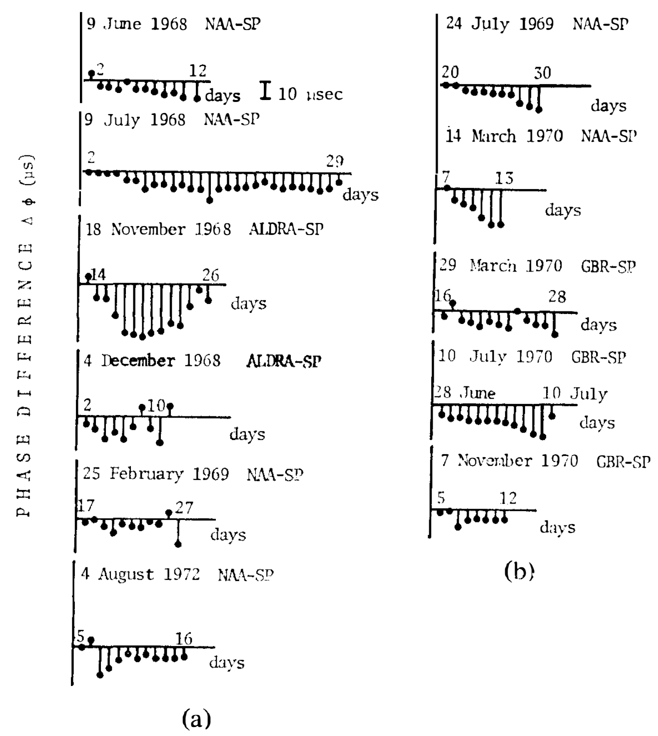

Fig. 6. Corresponding diurnal phase shifts on non-polar VLF propagation paths observed; (a) during the major events described in Section 3 and (b) during other PCA events or periods with high geomagnetic activity.

5. Conclusion

Based on the results obtained from the analysis of phase advances of VLF signals produced by PCA events in a transantarctic propagation path it was possible to conclude that:

(a) PCA events considered as weak or very weak can generally be clearly identified in the months from November to April.

(b) The events considered as strong with measurements at ground level even if observed from May to October are clearly defined.

(c) Phase deviations observed during weak events are apparently more directly related to the magnetic activity, or to precipitating protons of energy less than 10 MeV.

(d) Phase advance observed on the PCA of 6 June 1968 suggests that the reference height for the reflection of waves in the frequency of 15.5 kHz must be lower than that for waves propagating at 22.3 kHz.

(e) Strong or very strong PCAs can ionize the polar ionospheric *D*-region so efficiently to bring it down to altitudes as low as 45 km for reflection of VLF waves.

(f) Phase advances observed on VLF propagation paths that crosses the Anomaly during PCA's can provide means of detecting the trapped flux of particles penetrating into the lower atmosphere and identifying geomagnetic field perturbations because of its sensitivity to this kind of phenomena.

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