Burst precipitation induced perturbations on multiple VLF propagation paths in Antarctica

P. J. HURREN ([1]) (*), A. J. SMITH ([1]) (*), D. L. CARPENTER ([2]), U. S. INAN ([2])

([1]) *British Antarctic Survey* (NERC), *Madingley Road, Cambridge* CB3 OET, UK.
([2]) *Space Telecommunications and Radioscience Laboratory, Stanford University, California* 94305.

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ABSTRACT. The burst precipitation of energetic ($E > 40$ keV) electrons near $L = 4$ has been detected as amplitude perturbations (« Trimpi events ») on subionospheric 3.79 kHz CW signals from the Siple ($L = 4.2$) VLF transmitter that were observed at Halley ($L = 4.3$), Palmer ($L = 2.3$) and South Pole ($\Lambda = 74°$) Antarctic stations. The observations were made on the dayside of the Earth but beneath a locally dark ionosphere, during a generally disturbed 6 d period in July 1982 when the plasmapause projection was equatorward of the Siple-Halley and Siple-South Pole paths. Events detected at Halley showed similarities to Trimpi events previously reported on paths beneath the plasmasphere, but were of larger amplitude (1-8 dB, compared to typically 0.5-2 dB at lower latitudes), were time correlated with a wide variety of VLF noise forms in addition to whistlers, and were more variable in form and duration (up to 10-20 s). A minority of the events were observed simultaneously on two paths, and these tended to be associated with whistlers.

Key words : electron precipitation, amplitude perturbations, VLF propagation, wave-particle interactions.

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INTRODUCTION

There is a substantial body of evidence which suggests that coherent, magnetospherically propagating whistler-mode waves scatter energetic electrons into the ionosphere. The whistler waves are believed to interact with counterstreaming electrons near the equatorial plane, when the conditions for cyclotron resonance are fulfilled (Dungey, 1963; Cornwall, 1964). The experimental evidence includes ground observations of one-to-one correlations of magnetospheric VLF waves with X-rays (Rosenberg *et al.*, 1971; Foster and Rosenberg, 1976; Rosenberg *et al.*, 1981), with optical emissions (Helliwell *et al.*, 1980; Doolittle and Carpenter, 1983), and with perturbations in the amplitude and phase of sub-ionospherically propagating VLF signals (Helliwell *et al.*, 1973; Lohrey and Kaiser, 1979; Dingle and Carpenter, 1981; Carpenter *et al.*, 1984; Inan *et al.*, 1985). These observations complement those in which electron precipitation bursts detected on a rocket (Rycroft, 1973) or satellite (Voss *et al.*, 1984) coincided with whistlers received on the ground.

Precipitating electrons of energy > 40 keV can penetrate to *D*-region altitudes (Rees, 1969; Banks *et al.*, 1974). The secondary ionization thus produced can enhance the conductivity at the upper boundary of the earth-ionosphere waveguide sufficiently to lower the nighttime VLF reflection height (~ 85 km) and perturb the amplitude and phase of a VLF signal propagating within the waveguide (Inan *et al.*, 1985). Rapid signal amplitude and phase perturbations, caused by the burst precipitation of energetic electrons into the nighttime *D*-region, have been named « Trimpi events » after their discoverer. Initial studies found them to be characterized by an onset time of 1-2 s and a decay time of ~ 30 s (Helliwell *et al.*, 1973).

Previous investigations of wave induced burst precipitation, as revealed by VLF amplitude and phase perturbations, have in most cases focused on Trimpi events occurring equatorward of the plasmapause projection, and with sub-ionospheric signal sources which were at tens of megametres distance from the receiver or were located at relatively low magnetic latitudes (e.g. Carpenter *et al.*, 1984). However, in a recent series of experiments (Carpenter *et al.*, 1985), the Siple, Antarctica experimental ELF/VLF transmitter located at 76 S, 84 W, $L = 4.2$, was used with the configuration of great circle paths to nearby receivers at Palmer (65 S, 64 W, $L = 2.3$), Halley (76 S, 27 W, $L = 4.3$) and South Pole stations shown in figure 1. This network is capable of probing extended regions near to and poleward of the plasmapause projection, thus providing information that is complementary to that obtainable from other sensors at the stations. The network has the advantage of extended periods of darkness in the austral winter. Darkness

(*) Present address : Department of Physics, University of Sheffield, Sheffield S3 7RH, UK.

at the ~ 85 km VLF reflection height has been confirmed to be a major factor in the detectability of lower latitude events (Leyser *et al.*, 1984).

In this paper we study Siple signal amplitude data acquired at Halley during a 6 d period in July 1982. We describe features of the amplitude perturbations observed on a day of particularly strong Trimpi activity, note the variety of magnetospheric wave phenomena associated with the perturbations, and make some preliminary comparisons of the Halley data with those from Palmer and South Pole.

DATA SOURCES AND EXPERIMENTAL METHOD

We have used broad-band VLF data recorded at Halley, South Pole and Palmer stations during the period 12-17 July 1982. On these 6 consecutive days the transmissions from Siple consisted of long 3.79 kHz CW broadcasts between the hours of 13 UT and 22 UT, with short interruptions for other types of format (this 9 h period was designed to bracket local magnetic noon at South Pole when the station was in the vicinity of the cusp). There was good data coverage throughout the period at all three recording stations. Most of the Halley data were synoptic recordings made for 1 min in each 5 min interval.

We have examined all the available Halley data for the occurrence of Trimpi activity. For this purpose, a Trimpi event is defined as one in which the Siple signal amplitude exhibits a sudden (~ 1-2 s) change (of either sign) followed by a slower (> ~ 5 s) recovery towards the unperturbed level. In contrast to the situation at lower latitudes, we have found that such amplitude perturbations sometimes are not observed in clear association with whistlers or other magnetospheric VLF waves, and thus we have not required such an observed association as a criterion for inclusion in the Trimpi occurrence statistics.

A special scheme was developed in which long broadband tape recordings were automatically scanned for Trimpi activity. The output from the data tape was bandpass filtered (300 Hz bandwidth) at the transmitter frequency (3.79 kHz). After rectification and appropriate low pass (anti-alias) filtering, the signal was sampled and digitized at a 10 Hz rate and input to a data buffer in an on-line computer. The digitized time series was scanned for any rapid (< 2 s) changes larger than a preset threshold (1 dB); the algorithm was designed to discriminate against impulsive events with recovery times less than twice the onset time. For the 6 d period under study here, the automatic method was checked by plotting out all the data on paper chart and noting all events which subjectively appeared to have the characteristic Trimpi time signature. The automatic method had a ~ 90 % agreement with the visual method.

The available South Pole and Palmer data for the latter 3 d of the period were processed by the visual analysis of chart records, in order to make comparisons with the Halley data. These were the days on which most events were observed at Halley. In this paper we concentrate on the data for 15 July, since on this day the activity observed at Halley was largest both in terms of the size and the number of events.

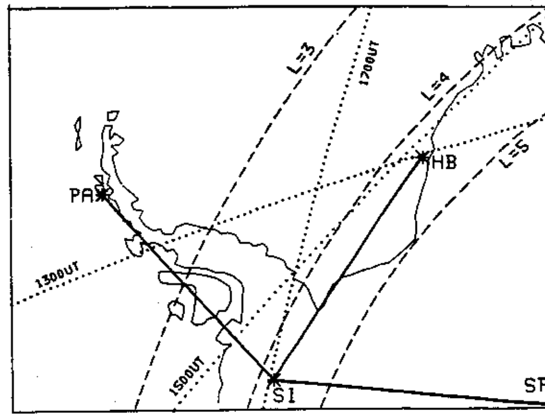

Figure 1

The network of great circle paths from Siple (SI) *to Palmer* (PA), *Halley* (HB) *and South Pole* (SP). *The terminators (at* 80 km *altitude) are shown by dotted curves for* 13 UT, 15 UT *and* 17 UT *on* 15 *July*.

RESULTS

In figure 2 we summarize the data coverage, Trimpi event occurrence periods, and magnetic disturbance conditions as represented by *Kp*. The period 12-17 July 1982 was generally disturbed, with a very large magnetic storm ($Kp = 9$) occurring on 13 July. From whistler evidence, the plasmapause was determined to be well equatorward of the Siple-Halley path, at $L \sim 3.5$.

Most events observed at Halley occurred in the latter 3 d of the period (see table 1), during a quieting trend,

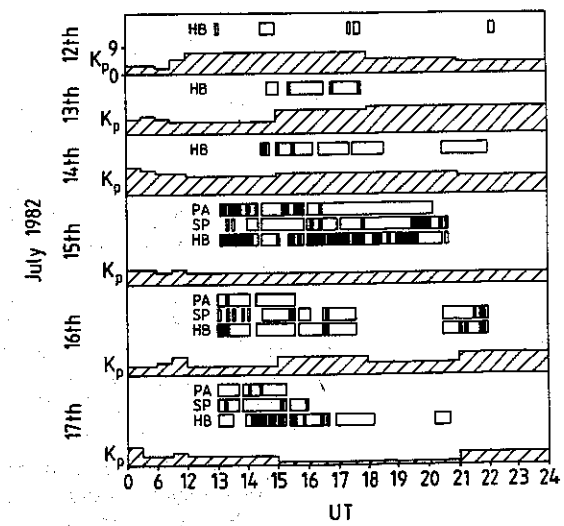

Figure 2

Summary of data coverage (open and solid boxes), Trimpi event occurrence periods (solid boxes), and K_p *values (cross hatched histogram) for the* 6 d *period of Siple* CW *transmissions. The time scale from* 0-12 UT *is compressed.*

Table 1
Trimpi occurrence statistics (Halley) July 1982.

Day	No. of minutes of data	No. of Trimpis
12	13	0
13	53	6
14	68	6
15	137	145
16	89	36
17	88	20

but still under conditions of moderate to severe magnetic activity. Occurrence rates varied from < 1/min to ~ 10/min. Both positive and negative amplitude perturbations were observed. Negative effects were generally more common, but positive changes were among the larger events detected, in terms of percentage amplitude change. Events of both signs were not observed within the same minute; episodes when all perturbations were of the same sign tended to last tens of minutes.

Since CW data are available only for 9 h dayside periods, limited information exists on the local time variation of the activity. We note, however, that most events occurred in the late morning to early afternoon sector i.e. before 18 UT (~ 15 MLT at Halley, ~ 13 MLT at Siple).

Figure 3 shows the number of Trimpi events observed at the three receiving stations in each half hour period on 15 July. The general decrease in Trimpi activity at Palmer in the 14-16 UT period is attributed to a terminator effect, i.e. that portion of the Siple-Palmer path where most burst precipitation is expected, outside the plasmapause projection at $L \sim 3.5$, becomes progressively more illuminated. At 1630 UT there is a cut-off in observed Trimpi activity at Palmer; the Siple-Palmer path is almost completely sunlit at this time. The Siple-Halley and Siple-South Pole paths, which remain in darkness (at 80 km) throughout the entire period, do not exhibit any such cut-off. The positions of the terminator at 80 km altitude for 13 UT, 15 UT and 17 UT on 15 July are shown in figure 1.

In figure 4, data from the minute 1930-1931 UT on 15 July are illustrated. Panels (*a*) and (*b*) represent the Siple signal amplitude as recorded at South Pole and Halley respectively : panel (*c*) shows the amplitude of VLF noise at Halley in the frequency range 0.5-2.5 kHz, whilst (*d*) is a 0-5 kHz spectrogram of the Halley data. The peak in amplitude at the start of panel (*b*) is caused by a calibration tone, which occurs at the start of each minute of Halley data. The simultaneous amplitude perturbations at South Pole and Halley are associated with the nearly coincident whistler clearly visible in figure 4(*d*) at 1930 : 33 UT, and in figure 4(*c*) as a short peak. The occurrence of similar events in neighbouring minutes (not shown) corroborates the association between the whistler and the perturbations.

This whistler-correlated event is similar in most respects to the event at 2145 UT on 16 July 1982, published by

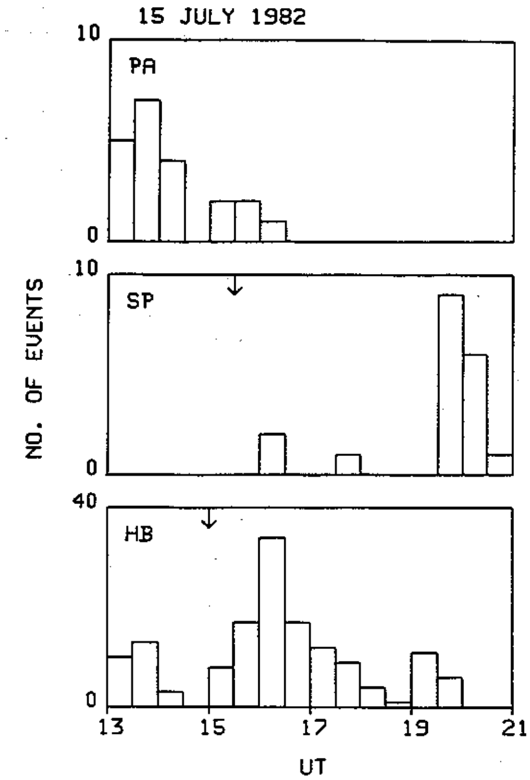

Figure 3
The number of Trimpi events on the 3.79 kHz *Siple signal observed at Palmer decreased sharply at* ~ 1430 UT *and cut-off at* 1630 UT *to* 21 UT *on* 15 *July* 1982. *There was almost continuous data coverage at the three receiving stations on that day. The observed Trimpi activity at Palmer decreased sharply at* ~ 1430 UT *and cut-off at* 1630 UT *(see text). The arrows mark magnetic local noon at South Pole and Halley.*

Carpenter *et al.* (1985). The two events are characterized by (*a*) an onset time (1-2 s) similar to that of lower latitude events in which precipitation occurs equatorward of the plasmapause projection; (*b*) a more rapid recovery time (~ 10 s compared to typically 30 s at lower latitudes); and (*c*) simultaneous perturbations at Halley and South Pole. The wave event closely resembles a type of whistler and associated triggered emission burst that has been found to be correlated with transient 4278 Å optical emissions detected poleward of the plasmapause projection (Helliwell *et al.*, 1980).

Whistler-associated Trimpi events during the 6 d period were in fact relatively rare, being observed only around 1930 UT on 15 July and 2145 UT on 16 July. Other Trimpi events were either correlated with other types of magnetospherically-propagating VLF signal or exhibited no clear correlation with magnetospheric VLF waves received on the ground.

Figure 5 shows an isolated positive Trimpi event which occurred on 15 July, ~ 2 h before the whistler-associated event described above. The upper panel shows the Siple signal amplitude at Halley during 1 min, whilst the lower panel is a 0-5 kHz spectrogram for the same data. The rapid (1-2 s) rise in Siple signal amplitude

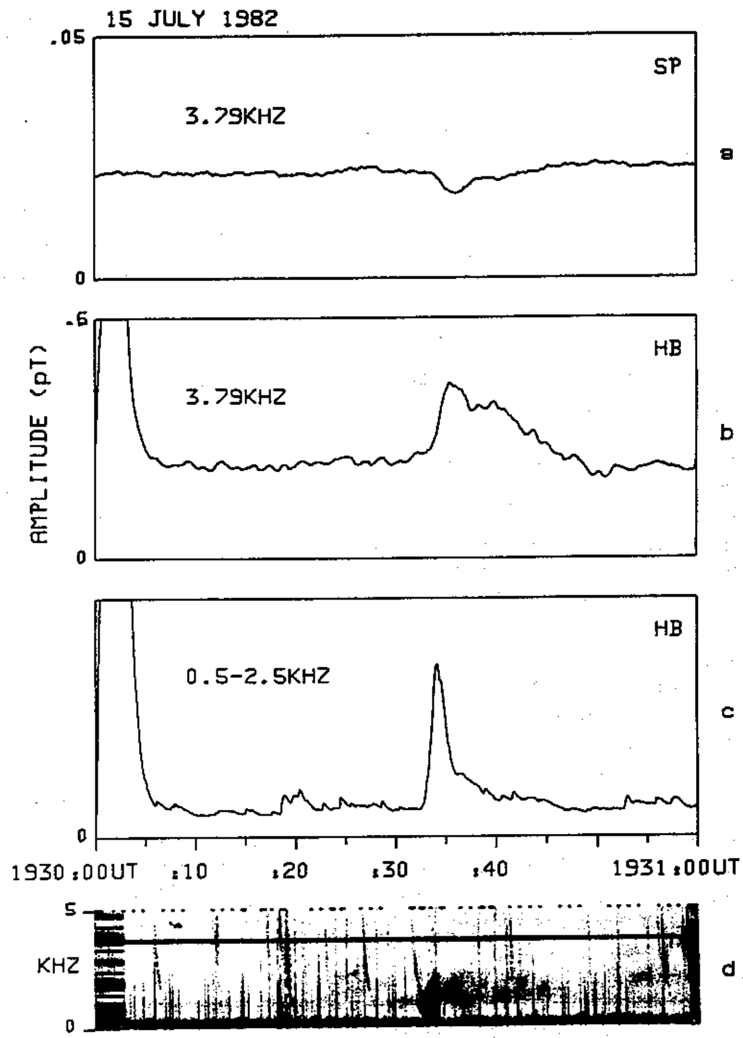

Figure 4
Simultaneous Trimpi events observed at South Pole and Halley during the minute 1930-1931 UT *on* 15 *July* 1982. *(a) and (b) : The Siple signal amplitude recorded at South Pole and Halley respectively; (c) : The amplitude of* 0.5-2.5 kHz *VLF noise at Halley; (d) : A* 0-5 kHz *spectrogram of the Halley data. (a), (b) and (c) were obtained from the* 0-10 kHz *data after band pass filtering, rectification, and low pass filtering (time constant* = 0.5 s*). The whistler in panel (d) at* 1930 : 33 UT *is observed as a short peak in panel (c), and is associated with the negative amplitude perturbation at South Pole and the positive perturbation at Halley. The large amplitude in panels (b) and (c) recorded during the first few seconds of the minute was due to a calibration tone at Halley, seen also in (d) as a multifrequency tone.*

by 3 dB, at 1710 : 08 UT, occurs nearly simultaneously with (within a second of) a group of three steeply rising emissions near 1 kHz, the third of which appears to trigger a burst of noise. Similar events in adjacent minutes strongly suggest a causal relationship between the onset of a VLF emission at ~ 1 kHz and a ~ 1-2 s rise in received Siple signal amplitude. After the rise the amplitude recovers more slowly (~ 5-10 s), as in the whistler cases, to its original level, but then undershoots to a still lower level, and finally recovers to its original level in ~ 30 s. A similar undershoot effect has been previously reported by Dingle and Carpenter (1981), however with a recovery time of 2-5 min. Undershoot effects were only observed on the Siple-Halley path.

In figure 6 we show three large positive Trimpi events which occurred within the same minute at Halley, 35 min prior to the event of figure 5. The first event at 1635 : 12 UT is similar to that of figure 5, except that the amount of undershoot is less. This event occurs in close time proximity to a multi-element riser which follows several risers of similar form. The riser appears to be triggered by a weak whistler. A second event at 1635 : 30 UT begins simultaneously with another multi-element emission, rises to the same level, but does not decay immediately. The high level is maintained for ~ 15 s, during which multi-element emissions occur repeatedly before a similar recovery occurs. The start of a third event is seen at 1635 : 57 UT. In this minute and adjacent minutes of data, the signature of a particular sub-ionospheric signal perturbation appears to be related to the structure of the associated VLF waves.

Figure 7 shows the Siple signal amplitude at Halley for 1 min in every five during the period 1620-1656 UT on 15 July. Although there are variations in many details, consistent features can be seen over this period. For example, positive perturbations in the 2-8 dB range are seen many times, and are always, during this period, in good time correlation with discrete emissions in the 0.5-3 kHz band. Sometimes there is structure on the rising edge (e.g. at 1630 : 35 UT) corresponding to structure in the VLF. A ~ 10 s recovery follows, but in several cases only after a period of irregular variation near the peak amplitude (1630, 1635, 1645 UT).

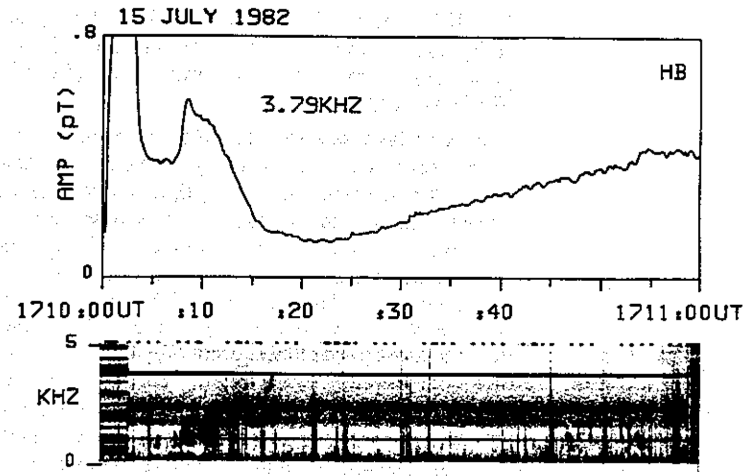

Figure 5
The positive amplitude perturbation at 1710 : 08 UT (upper panel) occurs within a second of a group of three steeply rising emissions and a noise burst near 1 kHz (lower panel). (An artificial horizontal line appears at 1 kHz). At ~ 1710 : 12 UT a large undershoot in signal amplitude commences and continues for 30-40 s.

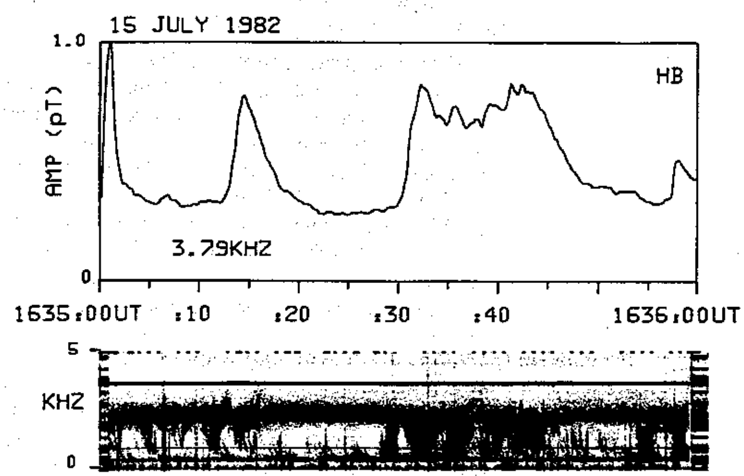

Figure 6
The signatures of the amplitude perturbations at 1635 : 12, : 30 and : 57 UT (upper panel) appear to be related to the structure of the associated VLF waves (lower panel). A high amplitude level is maintained during the second event, throughout which repeated multi-element rising emissions in the frequency range 1-3 kHz are observed.

The undershoot effect is seen several times (1645, 1655 UT). Occurrence rates can exceed 5/min (1625, 1650 UT); on the other hand no events occurred in the 1640 UT frame, and this corresponds to an observed temporary absence of magnetospheric VLF waves.

At other times during the study period, similar amplitude perturbations were associated with VLF phenomena of a different character, e.g. hiss bursts. On yet other occasions there was no clear correspondence with any VLF signal observed at the receiving station. An example is given in figure 8 : the top panel shows a characteristic negative Trimpi event observed at Halley. The bottom panel, representing the broadband 0-5 kHz data from Halley, shows a band of hiss near 1 kHz as well as risers similar in slope and frequency range to those illustrated in figure 6, but there is no apparent change in VLF activity near the onset of the perturbation.

DISCUSSION

The whistlers and VLF emissions correlated with the signal amplitude changes at Halley are generally similar to the wave events that have been found to be correlated with burst precipitation outside the plasmapause detected by X-ray measurements (Rosenberg *et al.*, 1971) and by optical techniques (Helliwell *et al.*, 1980). The fact that only a minority of the amplitude changes were associated with whistlers appears to reflect the special properties of the wave environment beyond the plasmapause, where structured emission activity dominates the spectrum, and the observed whistlers often trigger substantial releases of emission energy (Carpenter, 1978).

The fact that precipitation induced amplitude changes on the Siple signal have been observed even near local noon suggests that the Trimpi technique, using high geographic latitude paths in Antarctica, can be exploited during the austral winter for essentially 24 h probing of precipitation at $L > \sim 4$. The present data show relatively high levels of Trimpi event activity at the mid-morning beginning of the transmissions, and some tendency for the activity to diminish in the later afternoon hours (fig. 3). This diminution may be caused by a post-noon reduction of interacting particle fluxes due to losses of substorm injected electrons in the 0-

12 MLT sector (Pfitzer and Winckler, 1969), as well as by dayside increases in the equatorial radii of (low pitch angle) electron drift trajectories (Lyons and Williams, 1984).

Trimpi activity was seen on all three paths of figure 1. In general however, the activity on the three paths was not well correlated, suggesting that different magnetospheric whistler-mode paths and ionospheric precipitation regions were active simultaneously. In a minority of cases, simultaneous perturbations were observed either on the Siple-Halley and Siple-South Pole paths (e.g. fig. 4) or (less frequently) on the Siple-Halley and Siple-Palmer paths. These were mostly whistler-related events. Individual whistler sources have been found to excite multiple field aligned paths widely spaced in longitude (by up to ~ 30°, see Smith *et al.*, 1981) and *L*-value. This might result in time coincident precipitation bursts that are more widely distributed, and thus more effective in simultaneously perturbing multiple signal paths than bursts associated with VLF emissions that are not triggered by whistlers.

Simultaneous perturbations on two paths were often of opposite sign (e.g. fig. 4), and on the Halley path periods of both persistently positive and persistently negative events were observed on the same day. This is consistent with previous results on Trimpi events within the plasmasphere (Helliwell *et al.*, 1973; Carpenter and LaBelle, 1982). The spatial distribution of whistlers and emission activity observed outside the plasmapause, as inferred from intensities and frequency-time characteristics, is often substantially unchanged over periods ranging from minutes to tens of minutes, but on longer time scales may exhibit large and occasionally abrupt changes. These changes, which are not yet well documented, are probably reflected in temporal variations in the spatial distribution and intensity of burst precipitation activity, and hence in details of observed Trimpi events.

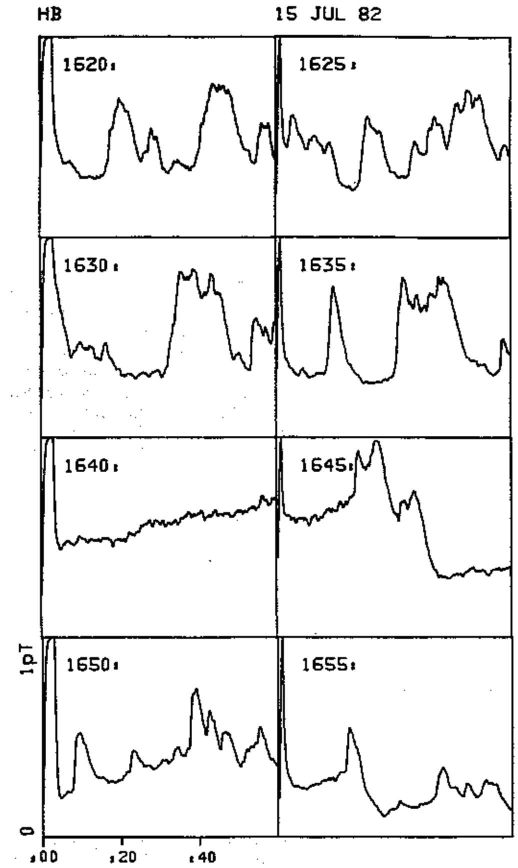

Figure 7
The Siple signal amplitude observed at Halley for 1 min *in every five from* 1620-21 UT *to* 1655-56 UT *on* 15 *July* 1982. *Each frame shows* 1 min *of data. See text for discussion.*

The effects were generally larger at Halley than at the other two stations; we interpret this as due to the location of the Siple-Halley path (fig. 1) at almost constant *L*. The ability of previous modelling work (Dingle, 1977; Tolstoy, 1983) to predict large events on relatively long (~ 10 Mm) sub-ionospheric paths depended critically on the location of the assumed precipitation region(s) with respect to the transmitter and receiver. If the situation is similar for the ~ 1.5 Mm paths of the present study, the geometry of precipitation regions necessary for large events to be observed is more likely to be realized on the Siple-Halley path than on the others. Reasons for this include the possible elongation in longitude of whistler ducts (Angerami, 1970) and the tendency for electrons capable of interacting resonantly with the VLF waves to drift along *L* shells. Furthermore, conditions for gyroresonant wave-particle interactions with $E > 40$ keV electrons are expected to be more favourable just outside the plasmapause than along path segments immediately equatorward of the plasmapause or well poleward of it.

Some amplitude perturbations at Halley were not associated with any observable change in VLF activity. In cases such as that of figure 8, magnetospheric VLF waves which triggered the perturbation may have been masked by other waves which were not associated with significant precipitation, or which induced precipitation that was not located so as to affect sub-ionospheric VLF propagation from Siple. Alternatively, the amplitude perturbation may have been caused by precipitation induced by non-ducted magnetospheric waves, which were not observable on the ground.

In events which exhibited a ~ 10-15 s long plateau in signal amplitude between the onset and recovery phases (e.g. fig. 6), the precipitation must have continued at a high rate in order to counteract the loss process, which typically involved signal amplitude recovery within ~ 10 s. The ability of the particle belts to sustain precipitation bursts lasting ~ 10-15 s suggests that the occasional undershoot effects, such as illustrated in figure 5, cannot readily be explained in terms of a depletion of trapped electrons near the loss cone (Dingle and Carpenter, 1981), unless there were significant time variations in the electron pitch angle distribution. A possible explanation of the undershoots is that during some precipitation events there were two effects, with opposing influences on the signal amplitude, such as an alteration in slope of the altitude profile

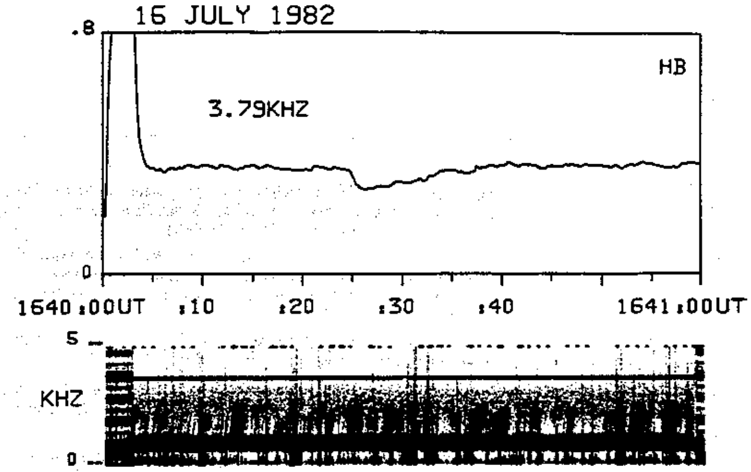

Figure 8
This Siple signal negative amplitude perturbation (upper panel) observed at Halley does not appear to coincide with any change in VLF activity (lower panel).

of electron density and a reflection height decrease (Inan *et al.*, 1985).

The data show evidence that the decay of excess ionization in the *D*-region, as inferred from the Trimpi event recovery times, was faster than the 30 s decays reported previously. While not yet explained, this difference would appear to suggest an altitude dependence of the decay rate, such that outside the plasmapause, the precipitation is on average more energetic and thus creates secondary ionization at slightly lower altitudes, where the neutral density is higher and the attachment rate of electrons to neutrals is faster.

CONCLUSIONS

A study has been made of amplitude perturbations (Trimpi events) on 3.79 kHz sub-ionospheric signals propagating from Siple, Antarctica to Palmer, Halley, and South Pole Stations, each about 1400 km distant. The observations were made on the local dayside during a 6 d period in the 1982 austral winter. Magnetic conditions were moderately to severely disturbed. Our findings include the following.

Sub-ionospheric VLF signals near 4 kHz propagating in the Antarctic on paths lying poleward of the plasmapause projection exhibited fast ($\sim$ 1-2 s) amplitude perturbations that are interpreted as resulting from wave-induced burst precipitation, but which differed in several respects from events of this nature observed on paths beneath the dense plasmasphere. The events poleward of the plasmapause projection appeared to reach greater amplitudes, often $\sim$ 6 dB, compared to values of 0.5-2 dB in the plasmasphere region. Both positive and negative changes were observed, as at lower latitudes, but the new cases were much more variable in duration, sometimes lasting 10-15 s before decaying. The occasional longer durations are attributed to another difference, the association with a wider variety of VLF noise forms, including whistlers, whistler-triggered emissions, chorus, and hiss, rather than predominantly with whistlers. The longer enduring events appeared to be associated with emission bursts of similar duration.

Post event undershoots of signal amplitude were observed, as in other work on burst precipitation outside the plasmapause. These did not occur persistently, however, and may be better interpreted in terms of changes in the ionospheric profile rather than as the result of a depletion of trapped electrons near the loss cone.

Event occurrences on the paths, which extend in widely different directions from Siple, were not well correlated. Most simultaneous perturbations on pairs of paths such as Siple-Halley and Siple-South Pole were associated with whistlers, which, because of their multipath excitation by lightning may tend to be associated with more widespread precipitation regions than are typical VLF emission bursts. Activity rates appeared to depend upon signal path orientation; rates were highest on the Siple-Halley path, oriented in the magnetically EW direction at $L \sim 4.3$.

The evidence suggests that the Trimpi technique can be used for essentially 24 h probing of precipitation at $L \geqslant 4$ in those west Antarctic regions that experience extended intervals of darkness at 80 km altitude in the austral winter.

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