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Journal of Atmospheric and Terrestrial Physics, Vol. 50, No. 2, pp. 105–115, 1988.
Printed in Great Britain.

0021-9169/88 \$3.00+ .00
Pergamon Press plc

The Siple VLF transmitter as a multi-frequency probe of the Earth–ionosphere waveguide

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(*Received in final form* 5 *August* 1987)

Abstract—1983 receptions of subionospheric signals radiated from Siple, Antarctica ($L = 4.3$) to neighboring stations Palmer ($L = 2.3$), Halley ($L = 4.3$), and South Pole ($\Lambda = 74°$), each ~ 1500 km from the horizontal (magnetically east–west) VLF transmitting antenna at Siple, were found to be strongly dependent upon azimuth and upon signal frequency. At Palmer, located equatorward in the broadside direction with respect to the antenna, signals near 2.5 kHz were often well defined, while the third harmonic of the transmitted signal, near 7.5 kHz, was not detected. Meanwhile, at Halley, the third harmonic was regularly observed and directionally stable, while the fundamental was often weak or undetectable. The field strength of the third harmonic component at Halley exceeded by ~ 40 dB the level of the fundamental, when both were normalized to the same antenna input power. The large size of these effects is attributed in part to antenna properties that favor the endfire direction (toward Halley) at the 3d harmonic of the antenna half wave resonance frequency, and in general provide greater efficiency at higher frequencies. Other factors are high waveguide attenuation in the 2–4 kHz range and azimuth dependent differences in the propagating modes. The observed effects represent a way of extending the effective frequency range of the narrowband Siple antenna system, and also, by using the new crossed dipole configuration at Siple, of selectively probing certain regions of the Earth–ionosphere waveguide.

1. INTRODUCTION

The experimental VLF transmitter at Siple station, Antarctica (76°S, 84°W, $L \sim 4.3$), has been used both for investigation of wave generation and propagation in the magnetosphere (e.g. HELLIWELL, 1983; HELLIWELL *et al.*, 1986) and, more recently, to probe the Earth–ionosphere waveguide near $L = 4$ for purposes of remotely detecting the effects of transient particle precipitation (CARPENTER *et al.*, 1985; HURREN *et al.*, 1986). A natural further application of the transmitter is the study of Earth–ionosphere waveguide propagation in the frequency range 1–10 kHz, for which no comparably equipped or located transmitting sources are available. Previous studies of this kind, while limited in scope, have been suggestive of the scientific potential of this type of probing. For example, MATTHEWS (1980) studied Siple signals near 4 kHz received at Halley from the 21 km antenna and, using formulas developed by WEBBER and PEDEN (1971), found the results to be consistent with the estimated ~ 1–2% antenna radiation efficiency (RAGHURAM *et al.*, 1974).

Exploratory transmissions were made in 1983 from Siple to stations Palmer, Halley and South Pole, each located roughly 1500 km from Siple (see map of Fig. 1a). This was done following lengthening of the horizontal dipole antenna at Siple from 21 km to 42 km. One of the outcomes of these experiments, as well as of receptions at the stations during other experiments, was the detection at Halley of large amplitude third harmonic components of the Siple signals. This was unexpected, since the antenna current waveform at the transmitter had been observed to be nearly sinusoidal, with a third harmonic content that was eventually measured to be 30–40 dB below the fundamental. Furthermore, third harmonic components were not detected at Palmer or South Pole, stations roughly the same distance as Halley from Siple.

A preliminary study was made of the limited available data on this effect (Siple station did not operate in 1984–1985), including results from special probing experiments that employed wide frequency ramps and pulses near the nominal half wavelength cutoff frequency of the waveguide of ~ 1.8 kHz. Large variations with frequency and path geometry were found in Siple signal reception at the three stations as func-

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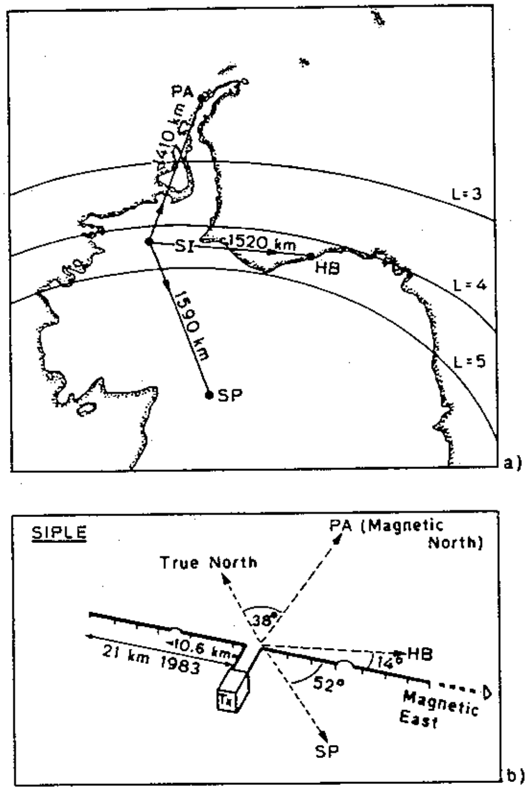

Fig. 1. (a) Map showing the network of Antarctic stations used in this paper, i.e. the transmitter at Siple (SI) and three receivers at Palmer (PA), Halley (HB) and South Pole (SP). (b) Sketch illustrating the great circle bearings from Siple to Palmer, Halley and South Pole, with respect to the geomagnetic east–west orientation of the dipole transmitting antenna at Siple. The extensions to the antenna installed in 1983, which doubled the dipole length from 21 km to 42 km, are shown schematically.

tions of frequency and of path geometry. Such variations are not unexpected; for example, WEBBER and PEDEN (1971), in discussing the problems of radiation from a short horizontal dipole in Antarctica, pointed out important differences in the nature of the modes radiated in the endfire and broadside directions.

In this paper we offer an initial report on the 1983 waveguide experiments, and briefly note some implications of the results for future research.

2. SIPLE TRANSMITTER CHARACTERISTICS AND OPERATIONS

Prior to 1983, the Siple transmitter operated into a single horizontal dipole antenna, oriented in the magnetic east–west direction as shown in Fig. 1a. The antenna was 21.2 km in length, with a half-wave resonant frequency $f_{res} \sim 5$ kHz. In 1983 the antenna was doubled in length to 42.2 km, with a half wave resonant frequency $f_{res} \sim 2.5$ kHz. In this paper we will refer to the 'short antenna' and the 'long antenna'.

In normal operations, transmissions are made at one or two controllable frequencies, which may be varied at 1 ms intervals within a narrow frequency range around a tuning frequency f_0. When f_0 is not equal to an odd multiple of the natural half-wave resonant frequency of the antenna (f_{res}), resonance is achieved by adding tuning elements in series. For most purposes it is desirable to transmit at nearly maximum power at f_0, and this restricts the operating bandwidth to typically ±250 Hz to ±500 Hz.

The impedance of the antenna (see for example RAGHURAM *et al.*, 1974) is such that when $f_0 \sim f_{res}$, significant power can be delivered to the antenna near $3f_0$. The frequency range around $3f_0$ is sometimes used for an 'idler', that is for a transmitted frequency at which a high power load on the generators can be maintained between pulses near f_0.

With the amplifier in use since 1979, the current waveform has under most circumstances been assumed to contain relatively little power at harmonics of the transmission frequency. During operations with the short antenna near maximum power and near 5 kHz, the output voltage waveform was found to be somewhat distorted due to the class AB operation of the power amplifier. However, the antenna current was very nearly sinusoidal, because of the relatively high Q of the antenna system.

3. OBSERVATIONS OF THE THIRD HARMONIC AT HALLEY

A strong third harmonic of the Siple transmission frequency was regularly observed at Halley during 1983, when the long antenna was in use for the first time. Most transmissions were at frequencies near 2.5 kHz (f_{res} for this antenna, and thus the frequency at which maximum power could be radiated). The third harmonic signals were usually observed near 7.5 kHz, as in the example of Fig. 2. In 1982 and earlier years, most transmissions were near 5 kHz (f_{res} for the short antenna) and any third harmonic would have been outside the passband of the Halley receiver (0.3–10 kHz). However, even on those occasions when lower frequencies were transmitted, at a reduced power, a third harmonic was hardly ever received.

Table 1 shows the occurrence statistics for 1982 and 1983 of the receptions at Halley of the fundamental and third harmonic of the Siple transmission frequency; these were obtained by surveying all available

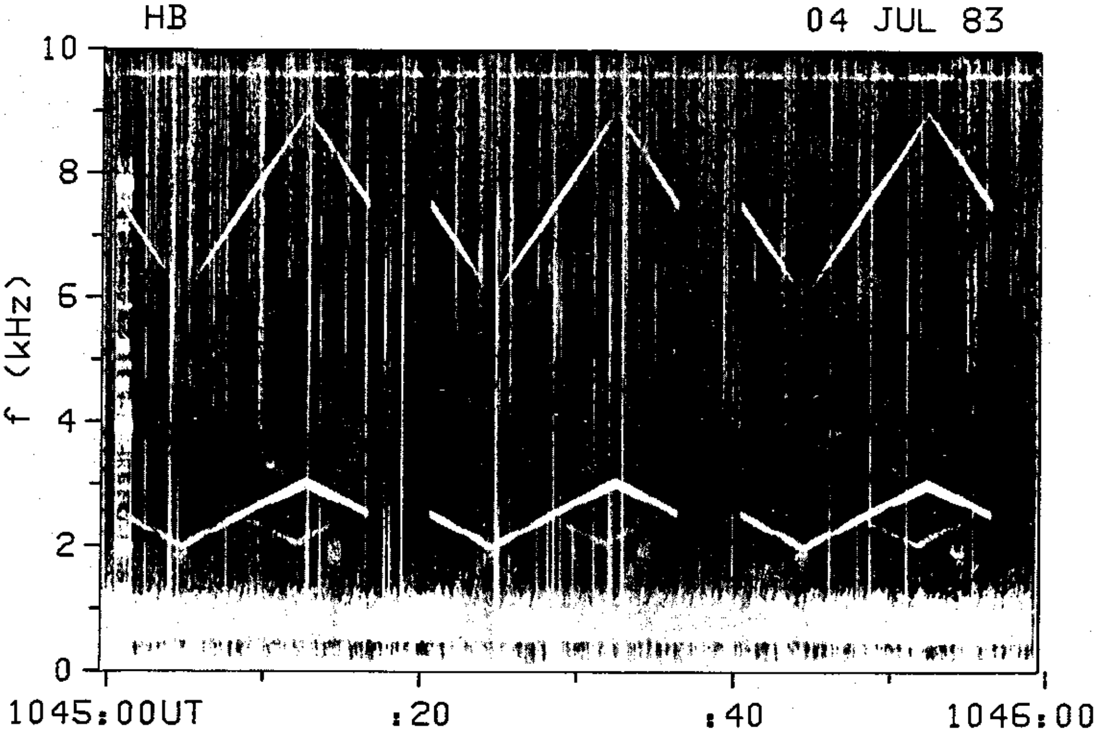

Fig. 2. Spectrogram showing an example of third harmonic reception at Halley on 4 July 1983 at 1045 UT. The transmission format consisted of frequency ramps rising and falling between 2 and 3 kHz. Both the fundamental (accompanied by a weak two-hop whistler mode echo) and the third harmonic, centered on 7.5 kHz, are clearly seen.

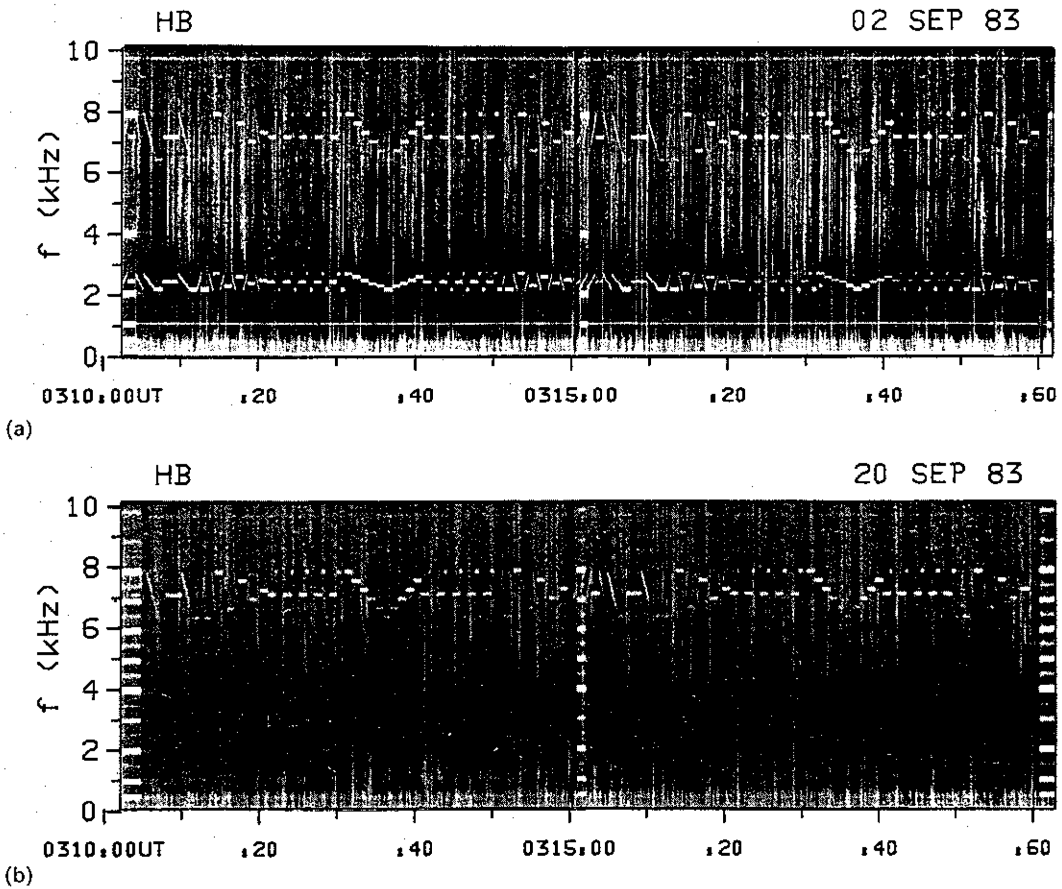

Fig. 3. (a) Spectrogram for 0310–0311 UT and 0315–16 UT 2 September 1983, showing another case in which both fundamental and third harmonic were received at Halley. (b) Similar to (a) but for a different day—20 September 1983. Local time and transmitter format were identical; antenna power and tuning frequency were almost identical. In this case however the fundamental was undetectable, though the third harmonic was received and appears to be of similar intensity to (a), relative to the spheric background.

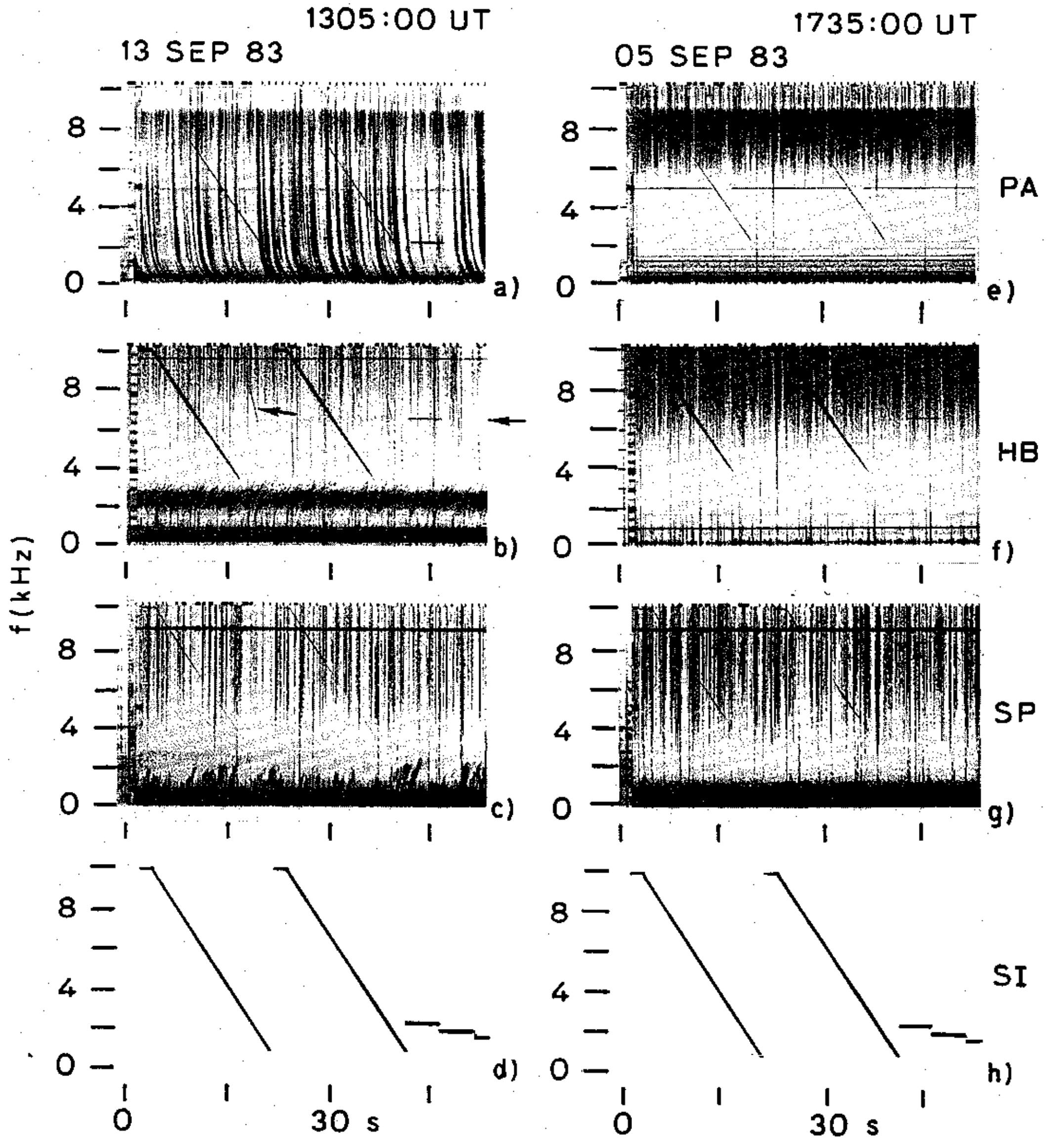

Fig. 4. (a) Palmer spectrogram for 1305–1306 UT on 13 September 1983, when Siple was transmitting the special wideband format shown in (d). The two ramps and the 2.2 kHz pulse were observed. The constant frequency signal at 5 kHz in this spectrogram and (e) is interference from a local source at Palmer. (b) The Halley spectrogram for the same minute. In the frequency range around 7 kHz ($3f_0$) the ramp fundamental was strong, indicated by a broadening of the trace, and third harmonics of part of the ramp (first arrow) and of the 2.2 kHz pulse (second arrow at 6.6 kHz) are visible. (c) South Pole spectrogram for the same minute. No third harmonic was seen. The fundamental was weaker than at Palmer. (d) The transmitter format. (e)–(h) as (a)–(d) but for 1735–1736 UT on 5 September 1983.

Table 1. Percentage of days when Halley received the fundamental and third harmonic of transmissions from Siple

	Year	
	1982	1983
Sample size (days)	23	83
No signals received	9%	1%
Only fundamental	82%	6%
Only third harmonic	0%	24%
Both fundamental and third harmonic	9%	69%

Halley recordings during which Siple was transmitting with $f_0 \leqslant 3.3$ kHz. After excluding a few cases characterized by strong natural noise at the frequencies of interest. the days were noted on which the fundamental and third harmonic were detectable, irrespective of transmitter power, bandwidth, etc. In 1983, a third harmonic was observed on 93% of the days surveyed. It was frequently more intense than the corresponding fundamental, which was not observed at all on about a quarter of the days.

Whereas the third harmonic signal observed at Halley in 1983 was generally strong and steady, the fundamental was highly variable in strength, both from day to day and also on any given day, when deep fading on a time scale of a few minutes was common. As an example, Fig. 3 shows 0–10 kHz spectrograms for Halley broadband VLF data taken on two different days. but at the same time of day. On these two occasions Siple was transmitting identical formats (consisting of a combination of pulses, frequency ramps and staircases) at nearly identical power and tuning frequency (108 kW, 2.36 kHz in Fig. 3a; 112 kW, 2.40 kHz in Fig. 3b). The third harmonic of the transmission format is clearly seen around 7 kHz in both Figs. 3a and 3b, and appears of similar intensity relative to the spheric background. By contrast the fundamental is clearly evident in Fig. 3a but undetectable in Fig. 3b.

A related observation concerns the apparent arrival bearing of the fundamental and third harmonic at Halley. The VLF receiver there is a goniometer (direction-finding) receiver (Bullough and Sagredo, 1973), which estimates the azimuth of arrival of received signals by measuring the ratio of two mutually perpendicular horizontal components of the wave magnetic field vector (H_x and H_y). The instrument gives a correct result for a single plane wave with its electric vector polarized in the plane of incidence; otherwise it is subject to polarization error (see Strangeways, 1980 for a detailed discussion of errors in the goniometer and other direction-finding systems). Measurements on Siple signals prior to 1983 (short antenna) have given results consistently within a degree or two of the great circle bearing of Siple from Halley (242°), examples at $f_0 \sim 3.7$ kHz having been reported by Matthews (1980). This is also true of measurements in 1983 of the third harmonic signal; on the other hand the apparent arrival bearing of the fundamental when $f_0 \sim 2.5$ kHz is sometimes highly variable (which is partly due to a poor and variable signal–noise ratio), and sometimes appears to have a polarization error of the order of 90°.

To give a quantitative example of the received intensities of the fundamental and third harmonic, we analysed a case on 24 May 1983 when the Siple transmitter was nominally radiating a continuous CW signal at $f = f_0 = 2.45$ kHz from the long antenna. Power input to the antenna was 60 kW. In spectra produced from the Halley broadband data, the peaks corresponding to the 2.45 kHz transmission frequency and its 7.35 kHz third harmonic were averaged over several 1 s intervals during the minutes 0055–0056 UT and 0355–0356 UT. These values were compared with the spectral peak corresponding to a calibration signal of known amplitude recorded on the data tape, giving results of 0.012 pT and 0.040 pT respectively for the rms wave magnetic field amplitudes. In Table 2 these results are shown converted to dB relative to $100\,\mu\mathrm{V\,m^{-1}}$ for the corresponding wave electric field. Also given are the results from similar measurements made on the broadband VLF data from Palmer and South Pole for similar times on the same day. At these stations, as was generally the case, the third harmonic component was undetectable. but it was possible to place an upper limit on its intensity by measuring the intensity of noise in a narrow band centred on 7.35 kHz.

For this typical case, the intensity of the third harmonic at Halley was ~10 dB greater than that of the fundamental. Any third harmonic at the other stations was at least 18 dB weaker at Palmer and 29 dB weaker at South Pole than it was at Halley. By contrast these two stations received a 15 dB stronger fundamental than Halley. Bearing in mind that all three receivers are roughly equidistant from the transmitter, these

Table 2. Absolute amplitudes of the fundamental and third harmonic of the Siple 2.45 kHz CW transmission on 24 May 1983, received at Halley, Palmer and South Pole stations (Units are in dB with respect to $100\,\mu\mathrm{V\,m^{-1}}$ rms)

		Station	
	HB	PA	SP
Fundamental	−29 dB	−14 dB	−15 dB
3rd Harmonic	−19 dB	< −37 dB	< −48 dB

results suggest a highly directional behaviour in the radiation and/or propagation of the third harmonic, and to a lesser extent, the fundamental, of Siple transmissions near f_{res} for the long antenna.

Measurements of the waveform of the antenna current at Siple showed very little harmonic distortion. With maximum power (150 kW) input to the short antenna at $f_0 = 4.87\,\text{kHz} \sim f_{res}$, the third harmonic content was about 43 dB below the fundamental (and 48 dB below at 4 kW). Only low power (19 kW) antenna current measurements were available for the long antenna. At $f_0 = 2.5\,\text{kHz} \sim f_{res}$, the third harmonic was down about 38 dB. A further opportunity to estimate the third harmonic content was provided by the special transmission format described in the next section. Following a 10 kHz to 1 kHz descending frequency ramp, a short pulse at 2.2 kHz (antenna power 51 kW) was transmitted and its third harmonic at 6.6 kHz was received at Halley at a field strength 24 dB below that of the signal received when the transmitter frequency was at the 6.6 kHz point on the ramp (and the measured antenna power was 16 kW). We can deduce that during the 2.2 kHz pulse, the ratio of the power supplied to the antenna at 6.6 kHz to that at 2.2 kHz was approximately $-24\,\text{dB} - 10\log(16/51)\,\text{dB}$, i.e. $-29\,\text{dB}$.

4. A WAVEGUIDE PROBING EXPERIMENT

At various times during September to November 1983 a special wideband format was transmitted from Siple, which consisted of frequency ramps descending slowly ($-0.5\,\text{kHz}\,\text{s}^{-1}$) from 10 kHz to 1 kHz, followed by three 5 s pulses at 2.2 kHz, 1.9 kHz and 1.6 kHz (see Fig. 4d). The intention was to study waveguide propagation to Palmer as a function of frequency, with emphasis upon behavior near the nominal waveguide half wavelength cutoff frequency of ~ 1.8 kHz. On occasion the transmissions were also recorded at Halley and South Pole.

In Figs. 4a, 4b, and 4c we show 0–10 kHz spectrograms of broadband data from Palmer, Halley and South Pole stations for 1305–1306 UT on 13 September 1983, when the special format (illustrated in Fig. 4d) was being transmitted. In the Halley spectrogram (Fig. 4b) the third harmonic of part of the ramp at 1305:21 UT (first arrow) and of the 2.2 kHz pulse that began at 1305:42 UT (second arrow) are clearly visible. At Palmer (Fig. 4a) only the fundamental of the 2.2 kHz pulse is seen. Figs. 4e–4h show data from 1735–1736 UT on 5 September 1983 in the same format.

Figure 5 shows results from the 13 September 1983 case; on this occasion f_0 was 2.33 kHz. The dashed curve shows measured power input to the Siple antenna as a function of transmitted frequency. As expected, the curve shows a maximum around f_0, and a second peak in the curve, centred on $3f_0$, is almost as large. The other three (solid) curves in Fig. 5 represent the variation of received field strength along the ramp at Halley, Palmer, and South Pole. They were obtained by playing the broadband tape recordings through a special laboratory tracking filter (Paschal, 1978) which, with suitable settings (of starting frequency, bandwidth, threshold for tracking, maximum and minimum slew-rate, etc.), was able to track on the ramp and produce an amplitude/frequency curve, provided that the signal–noise ratio was adequate. The frequency range of the curves of Fig. 5 is that for which it was possible to maintain accurate tracking. High levels of spheric activity at Palmer prevented tracking much above 6 kHz.

At Halley the received field strength for frequencies above 4 kHz was large compared to the other two stations, and followed the transmitter power curve fairly closely, although it is interesting to note that the Halley peak was closer to 7.5 kHz (i.e. $3f_{res}$) than to 6.99 kHz ($3f_0$). Below 4 kHz the received field strength fell off very rapidly with decreasing frequency to a point at which the tracking filter was no longer able to follow the descending frequency ramp. The curve suggests that at Halley, a signal in the $f \sim 2$–3 kHz range was received at an intensity more than 30 dB below that of a signal of similar antenna input power at $3f_0$. This is consistent with the observation described in the preceding section, in which the transmission frequency was near f_0 and a small ($\sim -30\,\text{dB}$) third harmonic component was received at Halley with a ~ 10 dB greater field strength than the fundamental.

The received signal at Palmer was much weaker than at Halley for the part of the ramp above 4 kHz. However, there is little evidence of a sharp lower cutoff frequency, as at Halley, and in fact the Palmer curve appears to reach a peak at or near f_0. At South Pole the received signal was much weaker again, but tracking was still possible because of the lower noise level. The frequency-dependent behaviour bears a limited resemblance to that at Halley, showing a lack of detection below ~ 3.5 kHz (see Fig. 4) and indications of increasing field strength near $3f_0$. The weak signal at South Pole relative to the other stations was probably due largely to the high attenuation rate of 15–25 dB per 1000 km for propagation over ice at ~ 4–8 kHz (Webber and Peden, 1971). A thick layer of ice (over rock), ~ 2000 m or more deep, extends over the entire

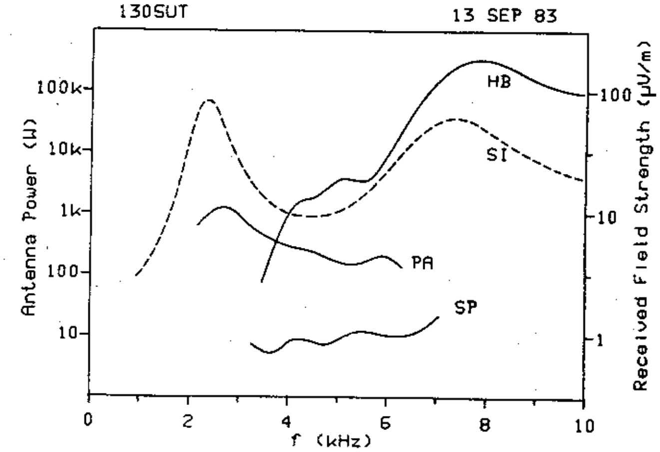

Fig. 5. The dotted curve (marked SI) and left hand scale represent the Siple transmitter input power to the antenna as a function of frequency during transmission of the format of Fig. 4d. The data were obtained from measurements made at the time of transmission and noted in the Siple transmitter operating log. The solid curves (marked HB, PA, SP) and the right hand scale indicate the corresponding received field strengths at Halley, Palmer and South Pole. They were obtained by analysis of the broadband data shown in Figs. 4a–4c, using a tracking filter to follow the descending frequency ramps. See text for further discussion.

Siple–South Pole path, but only over about a third of the Siple–Halley and Siple–Palmer paths.

Similar measurements to those described above were made on 5 September 1983 at 1720 UT and at 2020 UT, when f_0 was 2.37 kHz; the results were similar in general features to those shown in Fig. 5. All three of the intervals of ramp transmissions studied occurred under conditions of solar illumination above 80 km altitude along the three propagation paths. The Halley statistics reported in Table 1 covered both day and nighttime conditions, while the field strength values at the three stations presented on Table 2 represented nighttime. The data are insufficient for detailed day–night comparisons, but, where comparable, showed daytime values of 10–20 dB less than those for nighttime.

5. DISCUSSION AND CONCLUDING REMARKS

1983 receptions of subionospheric signals at three Antarctic stations, each located about 1500 km from the transmitter at Siple, were evidently strongly dependent upon azimuth and nominal transmitter frequency. At South Pole and in particular at Palmer, signals near the half-wave antenna resonant frequency of 2.5 kHz were often well defined, while the third harmonic of the transmitted signal, near 7.5 kHz, was not detected. Meanwhile, at Halley, the third harmonic was regularly observed and directionally stable, while the fundamental was often weak or undetectable, and when detected was often characterized by polarization error as determined from a crossed loop goniometer.

The large size of these effects suggests that factors having to do with waveguide propagation, mode excitation, and antenna pattern effects all play important roles. In the area of waveguide propagation, the phenomenon of the attenuation band near 3 kHz is probably important in explaining the weakness of the 2.5 kHz signals at Halley. Both theory (e.g. BUDDEN, 1961) and experiments with atmospheric sources (e.g. BARR, 1970a, b) reveal a pronounced attenuation peak near 3 kHz in waveguide propagation. In calculations of transpolar ELF/VLF propagation in daytime over ice, FIELD *et al.* (1972) found the least attenuated mode to suffer ~60 dB Mm^{-1} peak attenuation in a ~2 kHz-wide band centered at ~3 kHz, while experiencing only ~25 dB Mm^{-1} loss in the 5–10 kHz range. The lack of strong attenuation at 2.5 kHz at Palmer may be due to reduced attenuation near 3 kHz of the least attenuated QTE mode in comparison to the least attenuated QTM mode (BARR, 1974).

The unexpected strength of the third harmonic components at Halley, and their weakness elsewhere, is attributed in part to the Siple antenna properties. Both antenna image effects and the antenna radiation pattern can be visualized as contributing to the ~40 dB difference between signals at $3f_0$ and at f_0 at Halley. With regard to image effects, the antenna rests upon an ice sheet of ~2 km thickness which overlays a base of highly conducting wet rock (RAGHURAM *et al.*, 1974). In a design study for the first Siple antenna,

R. L. SMITH (1970) estimated the skin depth of the ice to be 14.4 km at 1 kHz, 6.1 km at 4 kHz, and 4.5 km at 10 kHz. Subsequent measurements by PEDEN *et al.* (1972) and ROGERS and PEDEN (1975) suggest somewhat smaller skin depths of approximately 7 km at 2.5 kHz, 4 km at 5 kHz, and 3 km at 10 kHz. On this basis, the radiation fields below 10 kHz may be considered to be roughly those due to a superposition of the Siple dipole plus its image located 2 km below the bedrock surface. For such a configuration, our calculations indicate that the net dipole moment of the antenna and image is proportional to f. Thus the dipole moment at the third harmonic is three times that at the fundamental.

With regard to the antenna radiation pattern, the following expression (JORDAN and BALMAIN, 1968) represents the ratio of the magnitude of the electric field radiated at $3f_{\text{res}}$ to that radiated at f_{res} in the plane containing the vertical direction and the horizontal dipole:

$$E_{(3\lambda/2)}/E_{(\lambda/2)} = \left[\frac{\cos[(3\pi/2)\cos\theta]}{\cos[(\pi/2)\cos\theta]}\right]$$

where θ = angle of elevation and the antenna current is assumed to be the same in both cases. For excitation of rays at ~10° elevation, appropriate for propagation of a one hop ray to Halley in the endfire direction, the value of the ratio is ~3. Hence the image and pattern factors can account for roughly 20 dB of the observed ~40 dB difference between $3f_0$ and f_0 at Halley.

For propagation in the broadside direction to Palmer, the pattern loss between f_{res} and $3f_{\text{res}}$ would be of order 3–5 dB. This and the roughly 10 dB increase in signal at Halley due to the pattern effect are consistent with the observed Halley/Palmer differences near 7.5 kHz, but fall short of explaining their magnitude of order 30 dB. Part of the 30 dB may be due to differences in the polarization of the received signals. At Palmer the signals may be predominantly horizontally polarized (TKALCEVIC, 1983), and thus inefficient (by as much as 10–20 dB) in exciting the vertical loop antennas used, while in the Halley direction, essentially vertical polarization and hence efficient antenna excitation may obtain.

These considerations suggest that there is much to discover and to understand about VLF propagation over high latitude ice-covered terrain in the frequency range below 10 kHz. The Siple antenna should be modeled at both its 21 and 42 km lengths, and as both a single element and in the (1986) two-element cross configuration. In subionospheric propagation studies, ray techniques (e.g. BERRY, 1964; TKALCEVIC, 1983) and mode theory (e.g. BUDDEN, 1961; WAIT, 1970; PAPPERT and SNYDER, 1972; FERGUSON, 1980; BARR *et al.*, 1986) should be applied to problems of propagation in the ~1–10 kHz range from Siple and from other locations, such as South Pole, where low power beacon type VLF transmitters might usefully be deployed in the future.

An important by-product of the reported experiments is the recognition that a higher frequency (3d harmonic) may under some conditions be available, both for waveguide probing, say of precipitation effects, and also for launching magnetospheric signals. The existing east–west dipole antenna has now been supplemented by a second, north–south, antenna with an independent frequency synthesizer. By appropriate excitation of the two crossed antennas, transmissions at f_0 and $3f_0$ may be 'beamed' in mutually orthogonal directions, either to excite whistler mode paths originating in selected regions, or to probe particular regions of the waveguide for precipitation effects. On some occasions, interhemispheric whistler mode propagations paths well equatorward of Siple may be probed by 3d harmonic signals radiated from the 42 km north–south antenna in the 6–9 kHz range, while right-hand circularly polarized waves at a fundamental frequency in the 2–3 kHz range are used to excite paths originating near the Siple field line ($L \sim 4.3$).

Acknowledgements—This work was largely carried out during a working visit to Stanford by the second author. It was supported by the Division of Polar Programs of the National Science Foundation under grants DPP83-17092 and 82-17820 and by the Natural Environment Research Council. We are grateful to T. WOLF and D. SHAFER for helpful discussions on the operation of the Siple transmitter, and to K. THURSTON for producing spectrographic illustrations from the Halley data.

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