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Anomalous noise from whistlers and radio atmospherics due to quasi-transverse electromagnetic mode propagation of VLF signals in the Earth-ionosphere waveguide

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Abstract. Observations of unusual VLF signals in the 0-4 kHz range are presented which appear to be band-limited segments of sferics and whistlers. These observations can be explained in terms of quasi-transverse electromagnetic mode propagation over long distances in the Earth-ionosphere waveguide.

Introduction

Observations of unusual VLF signals in the 0 - 4 kHz range that appear to be band-limited pieces of sferics and whistlers have been made at a number of continental United States (CONUS) and Antarctic sites. All the sites exhibit low power line harmonic hum, and through low-pass filtering (in the CONUS sites) or great distance from the transmitters (in the Antarctic sites) are little troubled by interference from OMEGA signals or intense nearby sferics. Sensitivity at the frequencies of interest (below 5 kHz) is thus enhanced. The noise has the appearance of narrowband pieces of whistlers or sferics, with the center frequency and bandwidth of the noise depending on the site location. The frequency range and spectral appearence of these unusual signals are unlike typical VLF signals in this frequency range, such as sferics, tweeks, chorus, hiss, power line harmonics, and whistlers.

The most striking examples of narrowband VLF noise are probably "whistler storms". This phenomenon was observed during the Aktivnyi campaign and reported by *Mielke and Mideke* [1991]. The authors do not know of any other reports of this phenomenon. These "whistler storms" show a number of unusual properties. Although frequently seen at low latitude, "whistler storm" elements have the spectral form of a high-latitude whistler. The "whistler storm" elements are also densely packed, rather more like chorus elements than like typical whistlers. These "whistler storms" tend to occur during the recovery phase of magnetic substorms, starting about local dawn and continuing for hours. Finally, they occur in a fairly narrow frequency band, below the Earth-ionosphere transverse electric (TE) and transverse magnetic (TM) waveguide cutoff frequency, with different sites showing different characteristic bands. Two hypotheses were suggested: that this phenomenon might be a novel sort of low-latitude chorus (M. Mideke, personal communication, 1989), or that large numbers of high-latitude whistlers were being observed at low latitudes (J. Yarbrough, personal communication, 1989). We find considerable evidence to support the second hypothesis. With typical VLF signals as sources, quasi-transverse electromagnetic (TEM) mode propagation over long distances in the Earth-ionosphere waveguide and reception on a small loop antenna can explain the observed spectral properties of this narrowband noise. In quantitative tests of this hypothesis, reasonable agreement is seen between calculated and measured values.

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Observations of Narrowband VLF Noise

A quiet site and sensitive receiver are required for observation of these "whistler storms". They have never been seen in spectrograms of the Stanford noise survey data (located in the foothills near Stanford University)

[*Fraser-Smith and Helliwell,* 1985] due to power line harmonic interference from nearby transmission lines. A much quieter site occupied during Aktivnyi satellite passes is China Grade, a logging road about two hours from Stanford University. Even at China Grade, the strongest "whistler storm" elements were at best only faintly visible through the power line hum. Most of the "whistler storm" observations reported here were made by one of the authors (Mike Mideke) at San Simeon, where his equipment is on a ranch far from power lines. Two examples of "whistler storms" were also found in the archived data from Siple Station, Antarctica, and one observation each was made at Elgin, Oregon (by Steve Ratzlaff) and at Paradise Valley, Nevada (by Steve McGreevy). Receiver sites are listed in Table 1 and shown in Figure 1. Unfortunately, no absolute measurement of "whistler storm" signal strength is available. The calibrated noise survey equipment has apparently never registered a "whistler storm" due to power line hum, the amateur receivers had no provision for calibration, and the one time China Grade data included a "whistler storm" no calibration tone was injected. About all that can be said is that even in rural areas "whistler storms" are weaker than typical power line hum. At China Grade, typical power line hum levels ranged from 0.18 μV m^{-1} Hz$^{-1/2}$ to 0.71 μV m^{-1} Hz$^{-1/2}$, measured in a 1-kHz band centered at 1.5 kHz.

Figure 2 shows spectrograms of typical "whistler storms". The curvature of the elements in the San Simeon data is not consistent with whistlers exiting the magnetosphere near San Simeon ($L < 2$). Dispersion analysis to obtain L-shell and equatorial electron densities [*Ho and Bernard,* 1973; *Park,* 1972] was performed on one prestorm whistler (included as a check on the technique) and 133 "whistler storm" elements. The "whistler storm" elements, taken from a 7 min period, were selected for their distinct nature (single trace, nonoverlapping), but otherwise were typical of the storm shown in the top two panels of Figure 2. The prestorm whistler was found to have an L-shell of 3.5 and an equatorial electron density of 422 per cubic centimeter. Nine "whistler storm" elements indicated L-shells so low that number density was estimated using the Smith model [*Helliwell,* 1965] and only L-shell information could be extracted. A histogram of "whistler storm" elements versus L-shell is shown in Figure 3. This shows a distinct peak around an L-shell of 4.7, where whistlers are relatively frequent [*Helliwell,* 1965]. Figure 4 is a plot of equatorial electron densities versus L-shell. The electron densities are reasonable values for the disturbed magnetic conditions [*Carpenter and Anderson,* 1992], with Kp of 5+ to 6- [*Coffey,* 1989] during the "whistler storm". The equatorial electron densities do exhibit considerable scatter, which is probably due to "whistler storm" elements coming from a wide range of longitudes, different longitudes having variations in the electron density for the same L-shell. Long distance propagation of whistlers from a wide range of longitudes also helps to explain the number of elements, visible in Figure 2 and far more numerous than generally seen in whistler data.

Table 1. VLF Receiver Sites

Location	Geographic Coordinates
China Grade	37°13′N, 112°13′W
Elgin	45°N, 117°W
Palmer Station (PA)	64°34′S, 64°3′W
Paradise Valley	41°N, 117°W
San Simeon	35°45′N, 120°18′W
Siple Station (SI)	75°55′S, 83°55′W
South Pole (SP)	90°S
Stanford	37°25′N, 122°11′W

Another feature visible in Figure 2 is the higher frequency and greater width of the band in which "whistler storms" are seen at San Simeon, California compared to Siple Station, Antarctica. It is shown below that for TEM mode propagation the peak power occurs at a frequency which varies directly as waveguide conductivity and the square of waveguide height and inversely as the square of source distance. Thus different sites with different characteristic distances to typical sources and differing conductivities of the intervening terrain are likely to exhibit different characteristic frequency bands in which "whistler storms" occur.

Instrumentation and Observational Criteria

The data in this paper were recorded on four different system designs. The RS-3 receiver [*Mideke,* 1989] was used at San Simeon and Paradise Valley. The VLF preamp and line receiver [*Helliwell and Katsufrakis,* 1978] was used at Siple Station, South Pole Station, and Palmer Station. The VLF radiometer [*Fraser-Smith and Helliwell,* 1985] was used at Stanford, and the portable VLF receiver [*Paschal,* 1980] was used at China Grade and, without WWV or GOES inputs, at Elgin. Block diagrams and frequency response curves for these receiving systems are shown in Figure 5. All systems have a flat response in the 1–5 kHz range where "whistler storms" are observed. The RS-3 receiver has no time

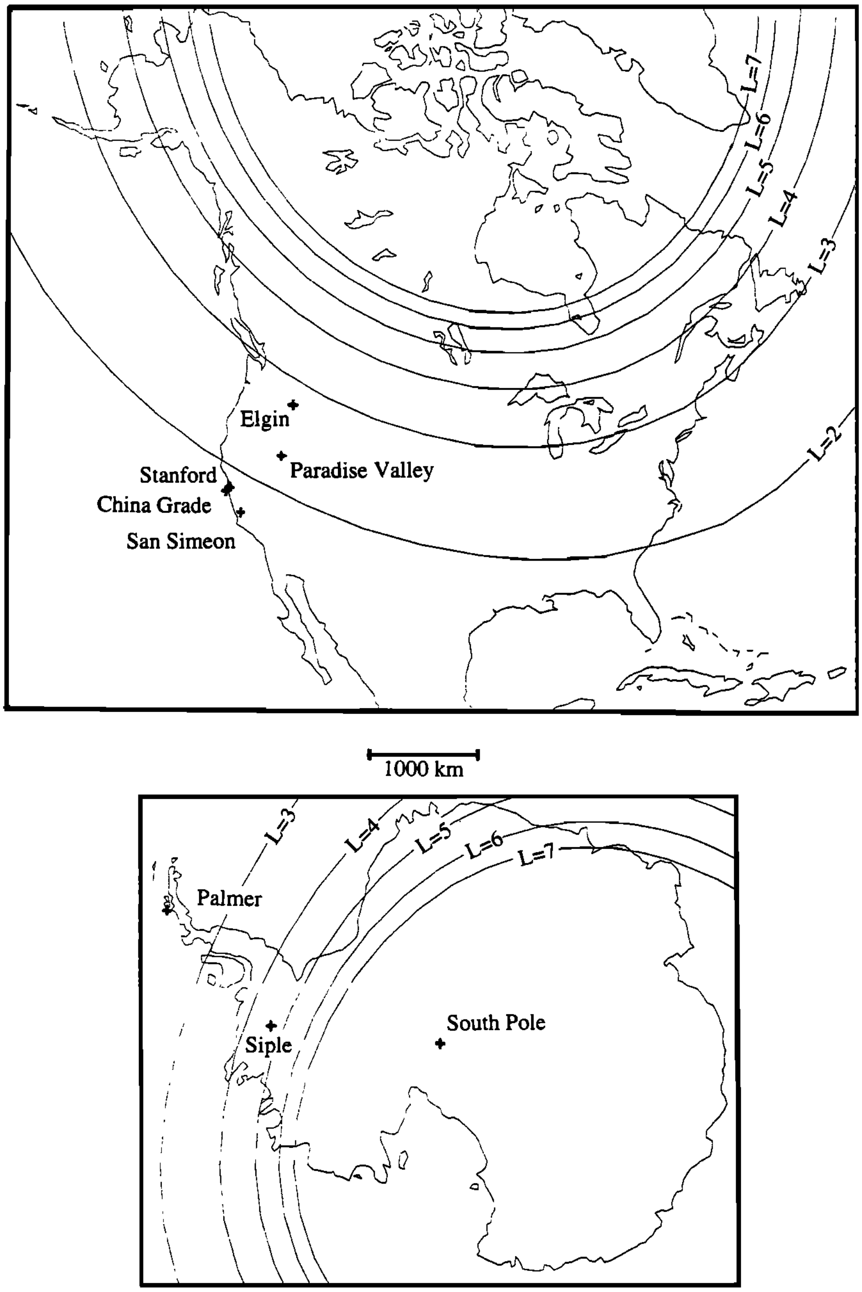


Figure 1. Map showing VLF receiver locations and L-shell contours. Whistlers (the presumed source of "whistler storms") are most common in the L=4 to L=5 range.

code injected, but on occasion it is possible to use the random pattern of sferics to register data from a RS-3 receiver with simultaneous data from a receiver with an injected time code. This procedure is rather like comparing fingerprints. As the Stanford system makes synoptic recordings only one minute out of each hour the technique is not always applicable.

Following Mideke's first "whistler storm" recording in August 1989 and the interest it provoked at Space, Telecommunications and Radioscience (STAR)

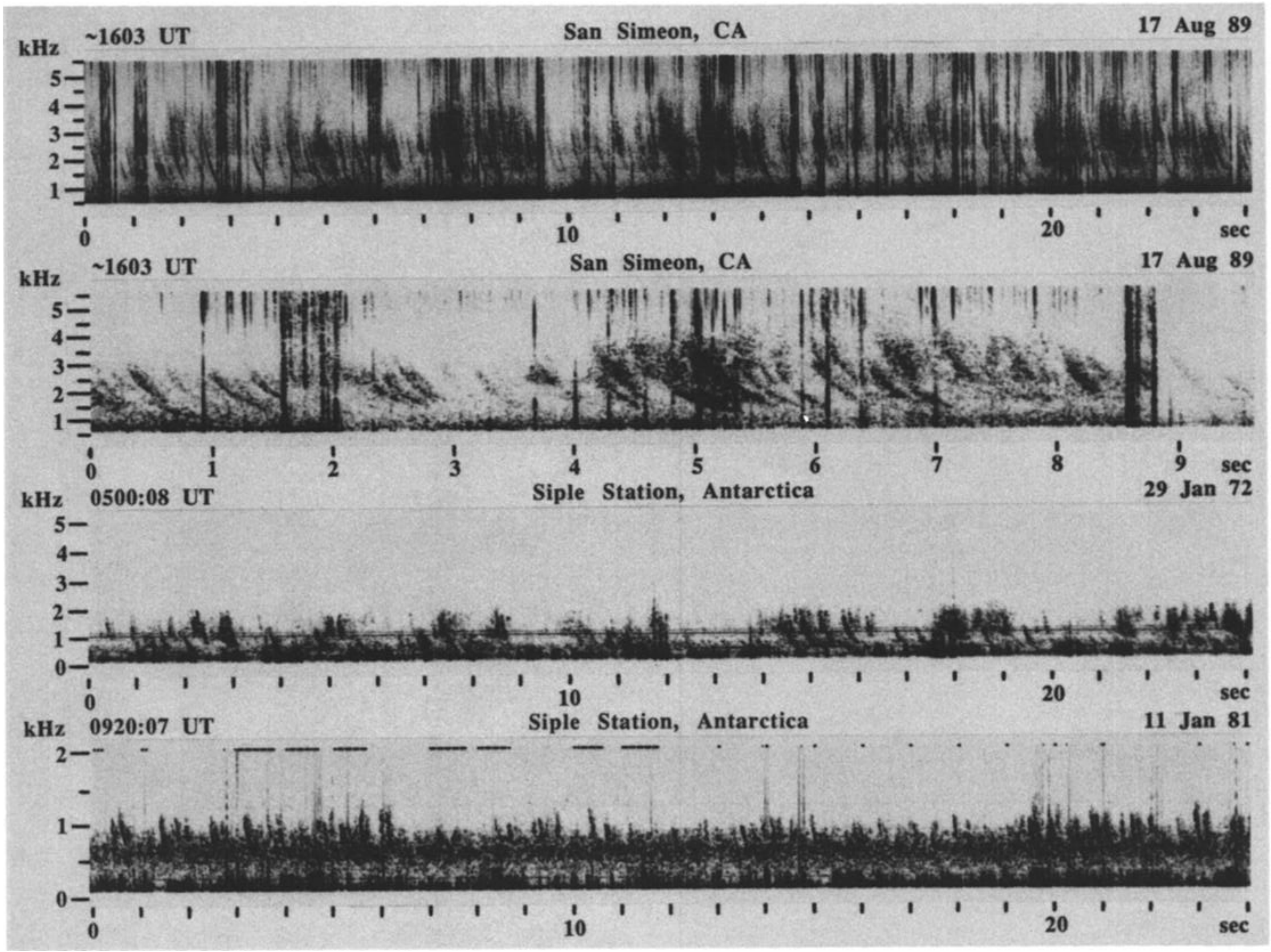


Figure 2. "Whistler storms". (upper two panels) "Whistler storm" observed at San Simeon, August 17, 1989 at ≈1603 UT and expanded version of the spectragram (used for scaling elements to obtain L-shells). Storm represented is typical of such phenomena, also observed November 30, 1989, December 3 and 26, 1989, January 1, 23, 25, and 31, 1990, and February 2, 1990. (lower two panels) Similar phenomena observed at Siple Station, Antarctica. Note that the frequency band of the Siple Station "whistler storms" is lower than that at San Simeon. The "whistler storm" elements are also densely packed, rather more like chorus (for which they were at first mistaken) than like typical whistlers.

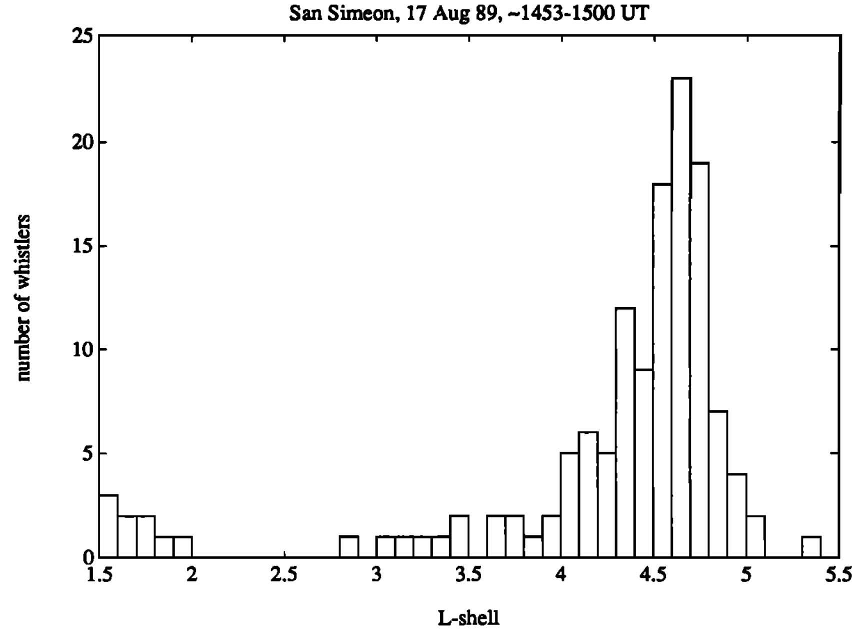


Figure 3. L-shell histogram for "whistler storm" elements observed at San Simeon, August 17, 1989, at ≈1453–1500 UT. The peak near L=4.5 is typical of whistlers, consistent with the hypothesis that whistlers are the VLF sources of "whistler storms".

Lab (Stanford University) later that year, Mideke's VLF monitoring became increasingly intensive, shifting from more or less casual dawn and late night checks to nearly around-the-clock operation of the VLF receiver. This program has continued into the present with only occasional interruptions. At a minimum, the status of ongoing natural VLF activity is logged morning and evening, with more intensive notes taken whenever activity is found to be unusual in any respect. Sample recordings are made if activity or changes in activity are deemed significent. When "whistler storms" and other protracted events (such as chorus) are in progress, note-taking and recording is generally carried out at frequent intervals. Every effort is made to follow the activity to its conclusion. Usually the pattern of ranch work can be adjusted to accommodate the observation of such events, but on occasion all-day town trips and other off-site demands do take precedence. While this approach to VLF monitoring cannot hope to capture every occurrence of "whistler storms", it should tend over time to reflect the actual distribution of these events.

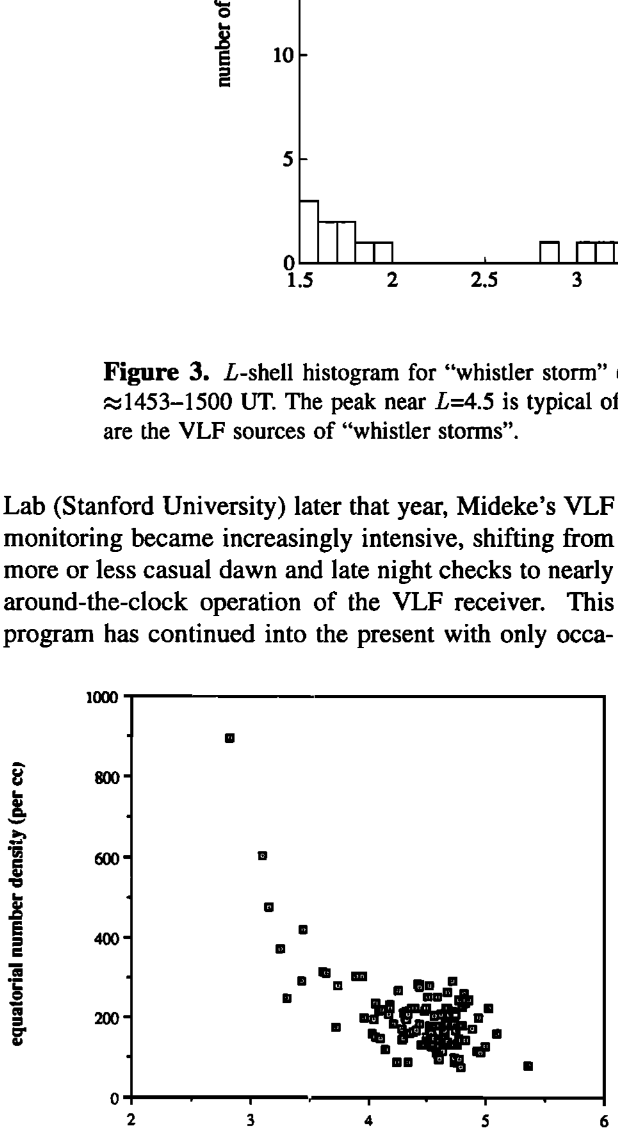


Figure 4. Magnetospheric plasma densities determined from "whistler storm" elements observed at San Simeon 17 August 17, 1989, ≈1453–1500 UT. This density profile is consistent with typical density profiles derived from satellite and whistler data.

The term "whistler storm" was coined by the authors to denote a class of persistent VLF activity characterized by its very high density of whistlers, most or all of which are confined within a severely restricted passband. Our working definition of the term encompasses whistler occurrence at rates of from 1 to 10 per second, a bandwidth ranging from roughly 1 to 5 kHz, upper cutoff frequencies between 1.5 and 5.5 kHz, and lower cutoff frequencies from 0.5 to 1.5 kHz. "Whistler storms", as observed at San Simeon, tend to show a

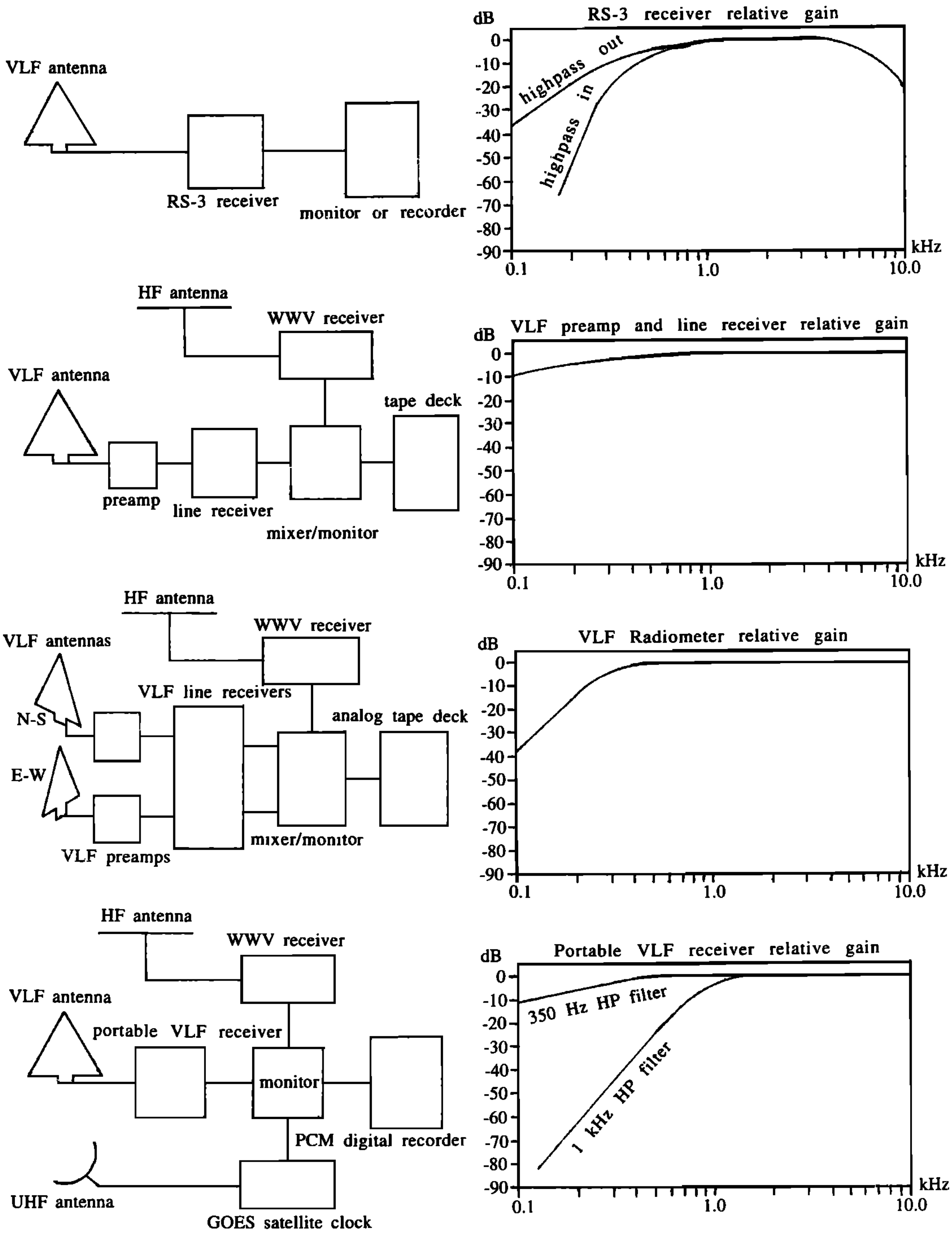


Figure 5. Block diagrams and frequency response curves for VLF receiving systems. Note that all systems have a flat response in the 1–5 kHz region where "whistler storms" are observed.

distinct pattern of evolution that begins with hiss and/or chorus in the predawn hours, followed by the appearance of densely packed band-limited whistlers sometime between first light and an hour after sunrise. As the day progresses, the whistler activity tends to become weaker and increasingly band-limited. The center frequency of the activity usually decreases, sometimes to the point of confining the whole "whistler storm" below 1.5 kHz. "Whistler storms" in their late phase are frequently very weak, often becoming no more than subtle modulations of a hiss band. A good deal of variation is to be found within this general pattern of "whistler storm" evolution. On occasion a full-blown "whistler storm" may appear abruptly. Sometimes elements typical of the late phase appear when no main phase has been detected. Chorus may appear simultaneously with the whistlers, or whistler and chorus activity may abruptly interchange. At any stage, the event may be intermittently subsumed by hiss. Fading is common, creating occasional confusion as to whether event sources, propagation, or both are changing.

Propagation Theory

The Earth-ionosphere waveguide is modeled as a flat metallic parallel-plate waveguide with lossy conductors. This approach yields considerable physical insight and straightforward mathematical forms while still providing fairly accurate calculations. With loss included the mode structures are somewhat modified, and the modes are called quasi-TEM, quasi-TE, and quasi-TM. A more sophisticated development of propagation in the Earth-ionosphere waveguide can be found in the work by *Budden* [1961].

From *Ramo et al.* [1965]: The TEM mode attenuation constant is given by

$$\alpha = \frac{R_s}{\eta a}$$

The TM mode attenuation constant (above cutoff frequency) is

$$\alpha = \frac{2R_s}{\eta a\sqrt{1-(f_c/f)^2}}$$

The TE mode attenuation constant (above cutoff frequency) is

$$\alpha = \frac{2R_s(f_c/f)^2}{\eta a\sqrt{1-(f_c/f)^2}}$$

The TE and TM mode attenuation constant (below cutoff frequency) is

$$\alpha = \frac{n\pi}{a}\sqrt{1-(f/f_c)^2}$$

where

R_s	surface resistance, equal to $(\pi f \mu/\sigma)^{1/2}$;
f_c	cutoff frequency, equal to $n/2a(\mu\epsilon)^{1/2}$;
a	plate spacing;
η	impedence of free space, equal to $(\mu/\epsilon)^{1/2} = 376.7\ \Omega$;
μ	permeability of free space, equal to $4\pi \times 10^{-7}$H/m;
ϵ	permittivity of free space, equal to 8.854×10^{-12}F/m;
n	mode number, equal to $1, 2, 3, \ldots$;
σ	conductivity.

From *Plonus* [1978], typical conductivity values (siemens per meter) are $\sigma = 4$ for seawater, $\sigma = 10^{-3}$ for wet earth, $\sigma = 10^{-5}$ for dry earth, and $\sigma = 10^{-6}$ for rock. A rough estimate of ionospheric conductivity, based on parameters from *Wait and Spies* [1964] is $\sigma = 10^{-1}$S/m.

Ionospheric height, equivalent to plate spacing, is taken to be 90 km at night and 70 km in daytime [*Helliwell*, 1965].

At the frequencies of interest (below 5 kHz) all the receiver antennas are effectively small loops. By Faraday's law, antenna terminal voltage goes as the time derivative of flux through the loop. Combining this with spreading losses in the (two-dimensional) Earth-ionosphere waveguide and with attenuation due to losses in the Earth-ionosphere waveguide, one obtains the following form for received power in a given mode:

$$P = (2\pi f A_{loop})^2 \frac{1}{l} e^{-2\alpha l} \propto \frac{f^2}{l} e^{-2\alpha l} \qquad (1)$$

with l equal to distance to source. In formula (1) the attenuation constant α includes the average R_s of both plates. In practice this average R_s is typically dominated by a single plate (ionosphere on a sea path, land on a land path).

Since neither source power for whistlers and sferics nor actual received power (much of the data set comes from observations made by amateurs using uncalibrated receivers) is generally available, the value of the constant of proportionality (which depends on antenna size, orientation, and on mode structure) is not required. For long paths and for frequencies below the higher-order TE and TM mode cutoff frequencies (about 2 kHz in daytime, 1.7 kHz at night) only the TEM mode contributes significently to received power. Often TE and TM modes suffer such high attenuation near their cutoff frequencies that sferics fade out at about twice the cutoff frequencies, as can be seen in the upper two panels of Figure 2. This is generally the case on land paths (where

Earth losses dominate day and night) and on sea paths in daytime (where ionospheric losses dominate). Under those circumstances, below 4 kHz (day) or 3 kHz (night) the contribution of TE and TM modes can be neglected. Tweeks, in which the waveguide cutoff frequencies and associated dispersion near cutoff are clearly visible are a notable exception, but also an easily recognized one! Received power from the TEM mode thus becomes:

$$P \propto \frac{f^2}{l} e^{-(\frac{\sqrt{\pi\epsilon}\sqrt{f}}{a\sqrt{\sigma}})l} \qquad (2)$$

which is shown in Figure 6. In equation (2) losses in one of the conducting boundaries are assumed to dominate, and σ is the smaller value of the ionospheric and land/sea conductivity. It is apparent that received power goes to zero at dc (due to the loop antenna response) and at high frequencies (where decreasing skin depth causes increasing surface resistance and consequent high waveguide attenuation). Setting the derivative of power with respect to frequency to zero leads to:

$$f_{maxpower} = \frac{16a^2\sigma}{l^2\pi\epsilon} \qquad (3)$$

Thus, location of the TEM "passband" depends directly on waveguide height squared, directly on waveguide conductivity, and inversely on the square of the distance to the source. This accounts for the narrowband nature of the observed noise as well as the lower frequency of the band in the Antarctic versus the CONUS data.

The importance of the TEM waveguide mode in understanding VLF phenomena is not new. In particular it was invoked to explain the "slow tail" effect seen in the time waveforms of some sferics [*Hepburn*, 1957; *Budden*, 1961]. Although hampered by the difficulty of spectral analysis circa 1960, this earlier research identified frequency-dependent attenuation in the TEM mode as critical to the "slow tails" and also pointed out the need for some mechanism to provide for dispersion in the TEM mode.

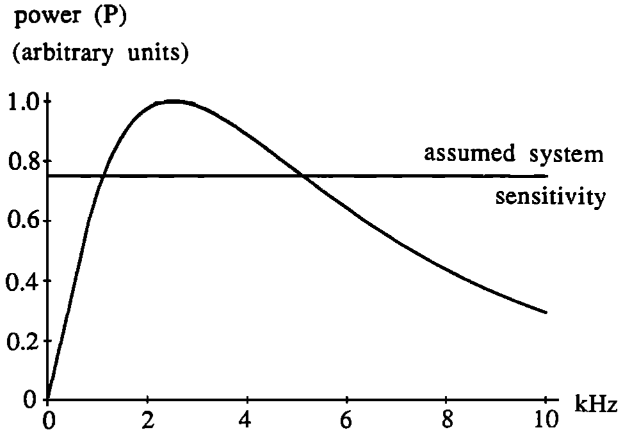


Figure 6. Received power from the TEM mode on a loop antenna. Note the band limiting effect for finite system sensitivity. Calculations used values of $l = 2000\ km$, $a = 70\ km$, and $\sigma = 3.5 \times 10^{-6} S/m$.

Observations and Interpretation

The higher frequency and greater width of the band in which "whistler storms" are seen at San Simeon, California compared to Siple Station, Antarctica (Figure 2) can be explained by the TEM mode propagation theory. With distance to the source estimated at 2000 km (from the L-shell information of Figure 4; see Figure 1), ionospheric height 70 km (daytime), and the "whistler storm" band taken to be 2.5 kHz, the conductivity of the land path between the whistler sources in Canada and the receiver in California is calculated to be 3.5×10^{-6} S/m using equation (3). This is approximately that of dry earth and is of the right order for a land path. Likewise, assuming that ice at 1 kHz is about as conductive as dry rock [*Bentley*, 1975], using the daytime ionospheric height (austral summer), and taking the "whistler storm" band to be centered at 1 kHz yields a distance to the source of about 1700 km for the January 29, 1972, Siple Station data. This number is also of the right order; whistlers exiting the magnetosphere over the Amundsen Sea (west of Siple Station) would cross about 1000 km of ice sheet on the way to Siple Station. Scaling of eight elements from the bottom panels of Figure 2 yielded L-shells of 2 to 6, with half of the elements at L-shells above 5. One might expect a "whistler storm" at Siple Station (L=4.5) to be a rare phenomenon, as it would require a respectable general level of whistler activity combined with very few whistlers at or near the station.

Figure 7 shows the time of day in which "whistler storms" occurred. In Figure 7 the phrase "event status unknown" indicates that the needs of running a ranch took precedence over monitoring a VLF receiver. The tendency of "whistler storms" to commence near local dawn (0700 PST = 1300 UTC) is evident. This can also be explained as a propagation effect; about dawn the electron density in the D-region of the ionosphere increases, lowering the reflection height of VLF waves and increasing the propagation loss. This moves the quasi-TEM "whistler storm" frequency band down in frequency and the quasi-TE cutoff up in frequency so that the lower attenuation quasi-TE Earth-ionosphere waveguide mode no longer masks the "whistler storm"

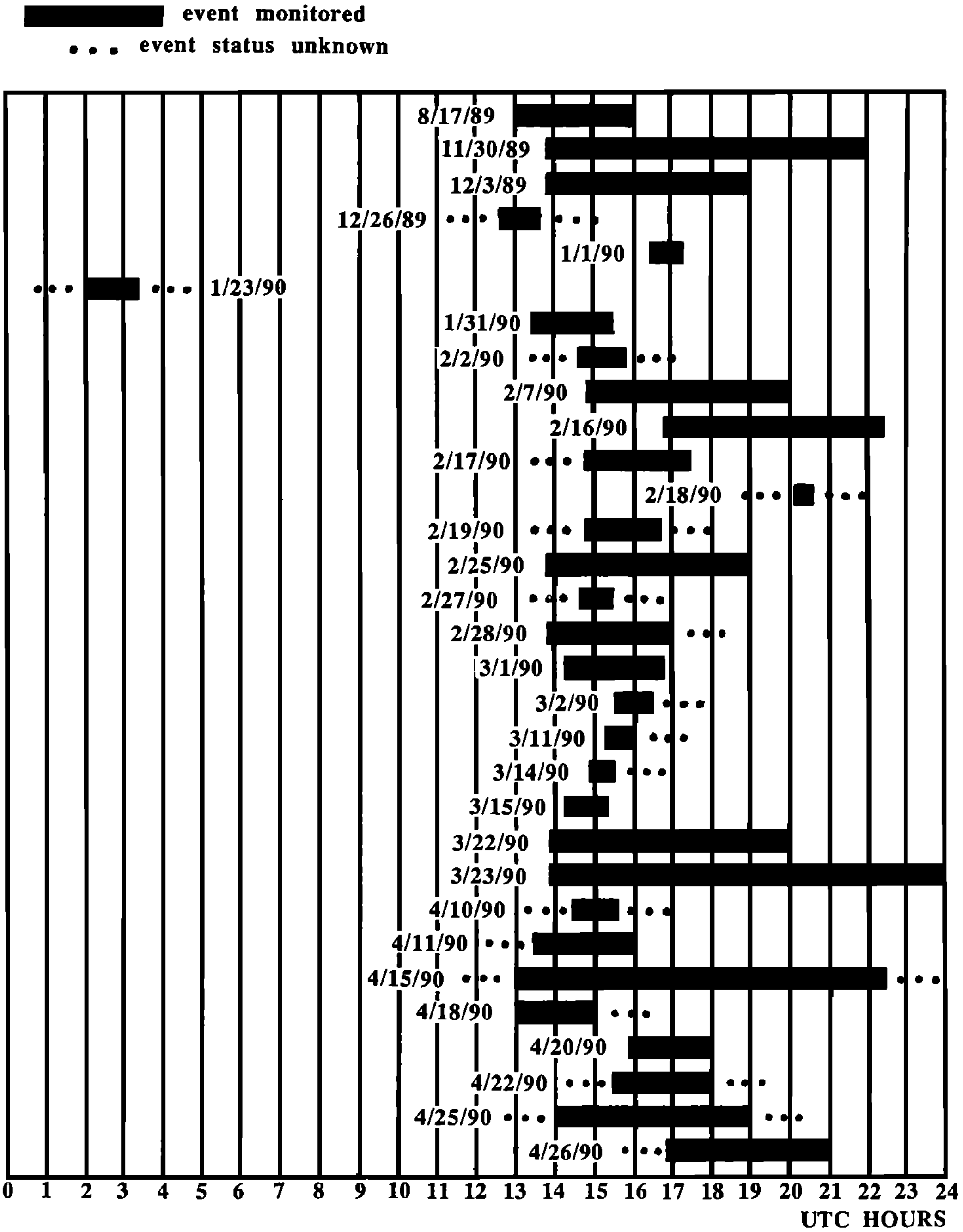


Figure 7. Commencement and duration of "whistler storms" observed at San Simeon. The tendency of the events to commence near local dawn (0700 PST = 1300 UTC) may be explained by the decrease in ionospheric height during the daytime which causes the maximum frequency of the received TEM mode to drop below the TE/TM cutoff frequencies. The TEM mode signals (if present) can then be observed unobscured by the generally much stronger TE/TM mode signals.

with sferics. To illustrate this, at San Simeon on August 17, 1989 (Figure 2) the "whistler storm" band is about 2 kHz wide, centered at about 2.5 kHz. It is daytime (1603 UT corresponds to 0803 PST) and the TE cutoff frequency is 2 kHz (waveguide height 70 km); few sferics have much energy below 4 kHz due to high attenuation near the cutoff frequency. The "whistler storm" is clearly visible. At night the waveguide height increases to 90 km. With all other variables held constant the "whistler storm" band rises to about 4 kHz while the waveguide cutoff descends to 1.7 kHz. Sferics with significant energy down to 3 kHz can now obscure the "whistler storm". Thus this model predicts that "whistler storms" would tend to commence near local dawn (if whistlers are widely present) and last until either dusk occurs or the lightning storms exciting whistlers cease.

Sferics with significant energy below the waveguide cutoff could also mask "whistler storms" day or night. Such sferics, which may be due to nearby lightning, can be seen in Figure 2 but are less common than sferics which fade out at twice the waveguide cutoff. It is possible that a whistler exiting the magnetosphere, which appears to illuminate a patch of ionosphere tens of kilometers in diameter [*Tsuruda et al.*, 1982], may couple to the quasi-TEM mode much more efficiently than does a lightning stroke of much smaller dimensions.

Even if lightning couples only weakly into the quasi-TEM mode, intense lightning would probably mask any "whistler storm" with sferics. One would expect therefore that "whistler storms" would be anticorrelated

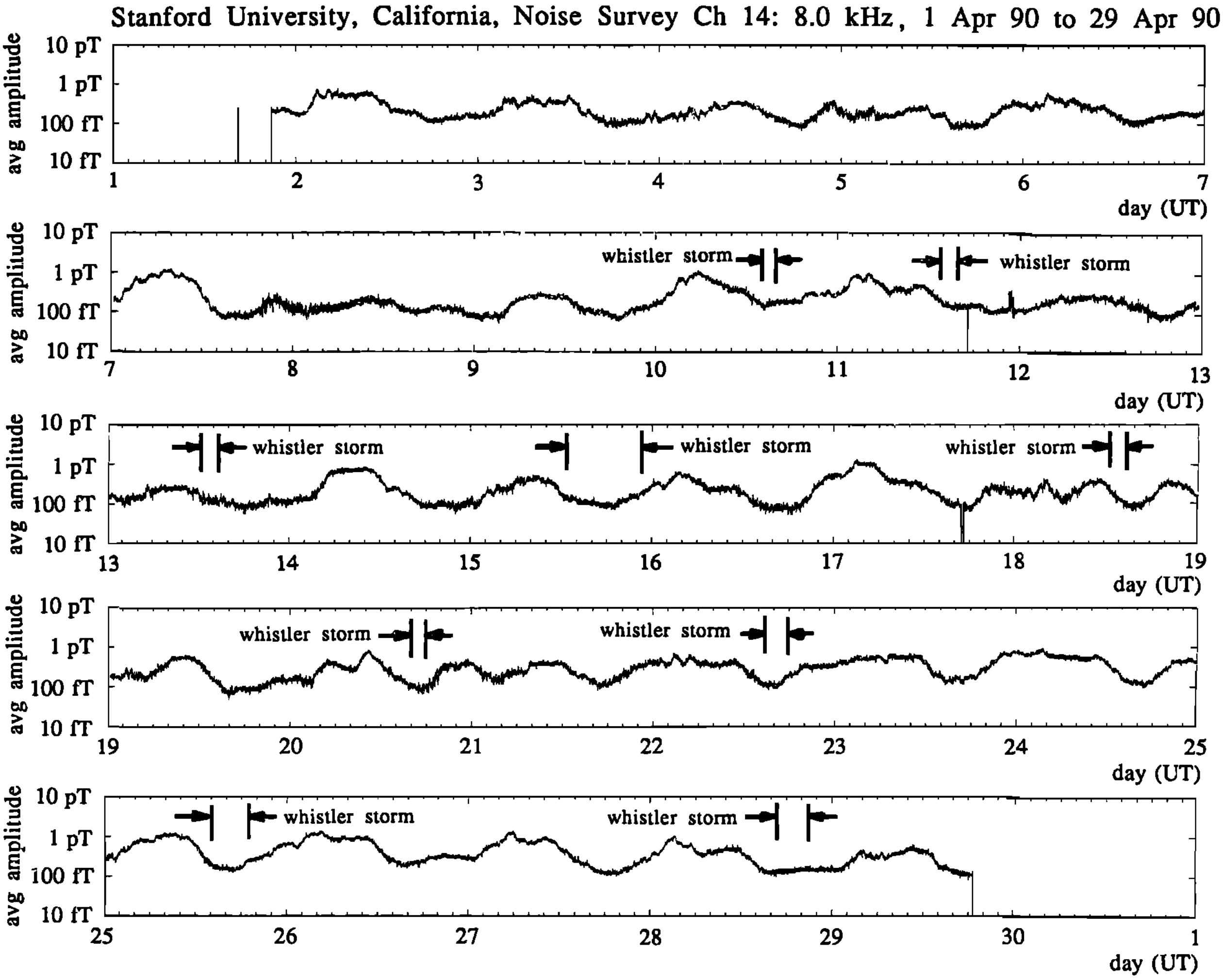


Figure 8. "Whistler storms" and atmospheric noise. The tendency for "whistler storms" to occur at atmospheric noise minima is probably due to normal diurnal variations in the ionosphere. This is consistent with the proposed "whistler storm" mechanism.

with noise levels (primarily due to sferics) measured by the Stanford noise survey [*Fraser-Smith and Helliwell*, 1985]. In Figure 8 the noise amplitude in the 8 kHz channel (selected as the best proxy for noise due to sferics) is plotted for the month of April 1990. There is a tendency for "whistler storms" to occur when atmospheric noise is low, but this may be due more to "whistler storms" tending to occur shortly after local sunrise (when the ionosphere also tends to become lossier, thus attenuating atmospheric noise) than to any

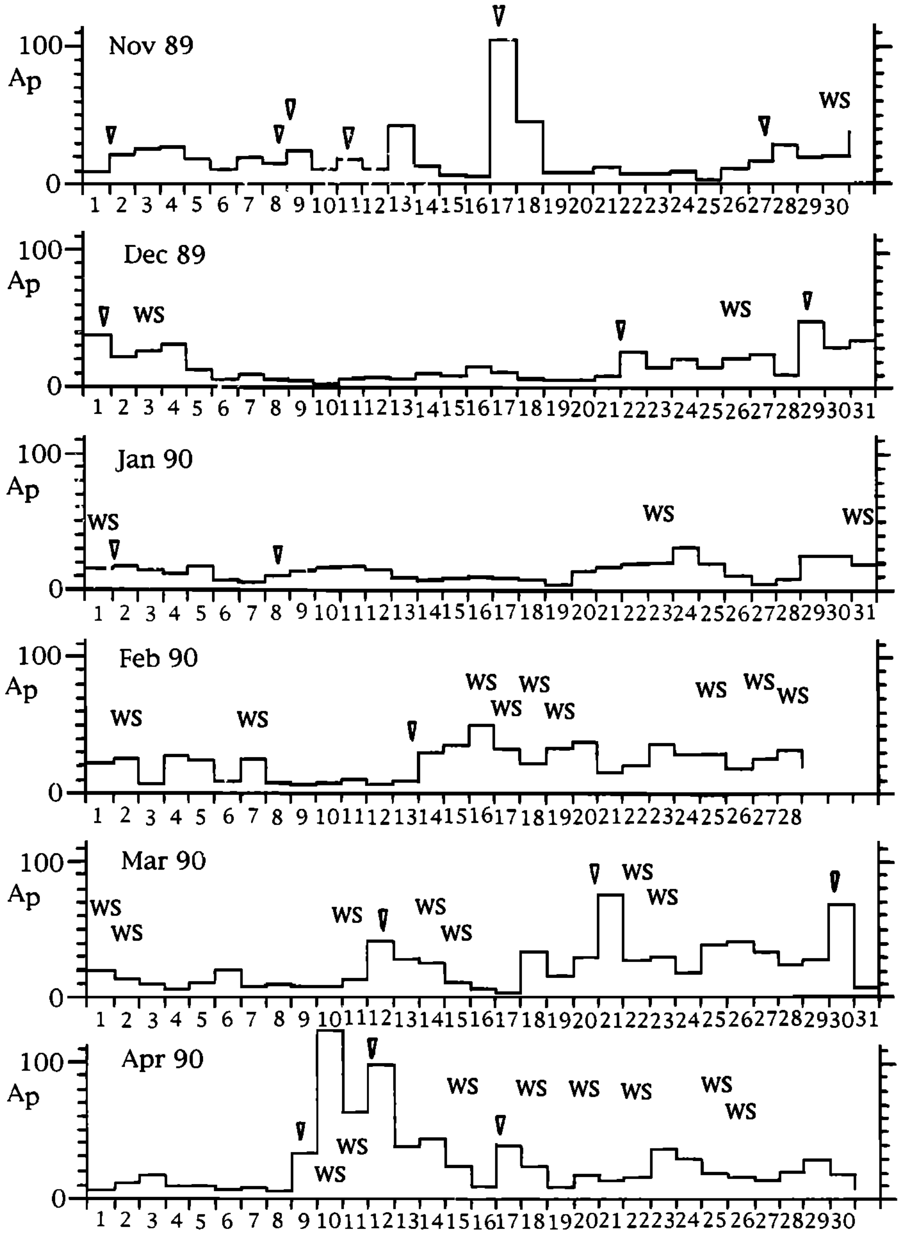


Figure 9. "Whistler storms" and geomagnetic variations. *Ap* is plotted for November 1989 – April 1990 [*Coffey*, 1990a], with sudden commencements [*Coffey*, 1990b, 1991] indicated by triangles and "whistler storms" indicated by the letters "WS". Intensive VLF monitoring began in late November 1989. "Whistler storm" episodes (clusters of "whistler storm" observations, with gaps of at most one day) tend to occur in the recovery phase of magnetic storms, as seen in 14 out of 16 cases. Whistler activity follows a similar pattern, which lends support to the proposed mechanism in which TEM propagation of whistlers causes "whistler storms".

reduction of thunderstorm activity on "whistler storm" days. Indeed, the days on which "whistler storms" occur do not appear at all unusual from the atmospheric noise standpoint when compared to other days of the same month.

A correlation between "whistler storms" and whistler activity is also to be expected in this model. No index of whistler activity could be found, so this anticipated correlation could not be checked directly. An indirect comparison can be made; whistlers tend to be both more numerous and stronger during the recovery phase of magnetic substorms [*Smith and Clilverd*, 1991; *Helliwell*, 1965]. One might therefore expect "whistler storms" to tend to occur at such times. Figure 9 illustrates the relationship between "whistler storms" and magnetic indices. One pattern appears to be predominant: On day 1 the *Ap* index is elevated over the previous day's, often in connection with a sudden commencement. On day 2 and following days the *Ap* index has usually decreased. Typically on day 3 (±1 day), and sometimes for several days in a row, there are "whistler storms" with moderate fluctuations in the *Ap* index. Intensive monitoring at San Simeon started in late November 1989, and 14 out of 16 "whistler storm" episodes observed between then and the end of April 1990 fit such a pattern. A "whistler storm" episode consists of one or more successive days on which "whistler storms" are observed, with gaps of one day permitted to allow for the vagaries of lightning, propagation conditions, and monitoring. The "whistler storm" episodes of November 30, December 3, and December 26, 1989, January 1, January 31 to February 2, February 7, February 16–19, February 25 to March 2, March 14–15, March 22–23, April 10–11, April 15, April 18–22, and April 25–26, 1990 illustrate the general pattern of occurrence following either a sudden commencement, or an increase then decline in *Ap*; the "whistler storms" of January 23, 1990, and March 11, 1990, are exceptions. Such similar patterns of whistler occurrence and "whistler storm" occurrence are consistent with "whistler storms" being due to long-distance TEM mode propagation of high-latitude whistlers.

Figure 10 shows observations of "whistler storms" at Elgin, Oregon, and San Simeon, California on May 27, 1990 and also at Paradise Valley, Nevada and San Simeon, California on August 22, 1990. On August 22, 1990, five minutes lapsed between observations; in the case of the May 27, 1990, observations there is a lapse of over four hours between recorded samples from the two sites. It is worthwile to note that the San Simeon log entry for 1300 UT (only 11 minutes after the Elgin "whistler storm" recording) notes only nontweeking sferics and scattered, weak, hollow sounding whistlers. "Whistler storm" activity was not noted at San Simeon until 1708, and recording commenced almost immediately upon that observation. As Ratzlaff had to leave his site while the "whistler storm" was still in progress, the duration of the event in Oregon is unknown. In central California it is best characterized as weak and brief. It is not clear whether the same long-lasting event was seen sporadically at both sites or whether different sporadic events were seen at each site.

In the case of the August 22, 1990, "whistler storm", our belief that the same event was recorded at Paradise Valley, Nevada, and San Simeon, California, is supported by the fact that the "storm" was logged at San Simeon at regular intervals (and recorded at least hourly) from 1333 to beyond 1800 UT. While no simultaneous recordings were made, the spectral characteristics of the California and Nevada tapes made around 1600 are highly similar, to the point where differences between them might be accounted for by normal minute-to-minute variations within the event. The reception of similar activity at these moderately distant sites does suggest that, rather than being some extremely localized and hard to explain oddity, the "whistler storm" phenomenon has much in common with other VLF signals that have traveled a considerable distance in the Earth-ionosphere waveguide.

VLF phenomena below 5 kHz can be difficult to observe. Figure 11 shows two sets of simultaneous data, from Stanford and San Simeon on August 17, 1989, and from China Grade and San Simeon on December 26, 1989. In both cases the sferics line up but power line hum at Stanford and China Grade prevents observation of the "whistler storm" clearly visible at San Simeon. One can just make out a few of the strongest "whistler storm" elements at China Grade, but all that these can do is confirm the San Simeon data. Although both sites were selected for their freedom from power line hum, "whistler storms" have never been noticed in recordings from Roberval, Canada or Lake Mistissini, Canada. This is probably due to equipment dynamic range limitations. If gain is set so that nearby sferics do not cause saturation of the receiver or recorder with attendant distortion, such weak signals as "whistler storms" would probably be missed.

It should be noted that the December 26, 1989, and May 27, 1990, "whistler storm" bands are centered near 1.5 kHz, somewhat lower than the ≈ 2.5 kHz center of the August 17, 1989, and August 22, 1990, "whistler storm" bands. With the daytime ionospheric height of

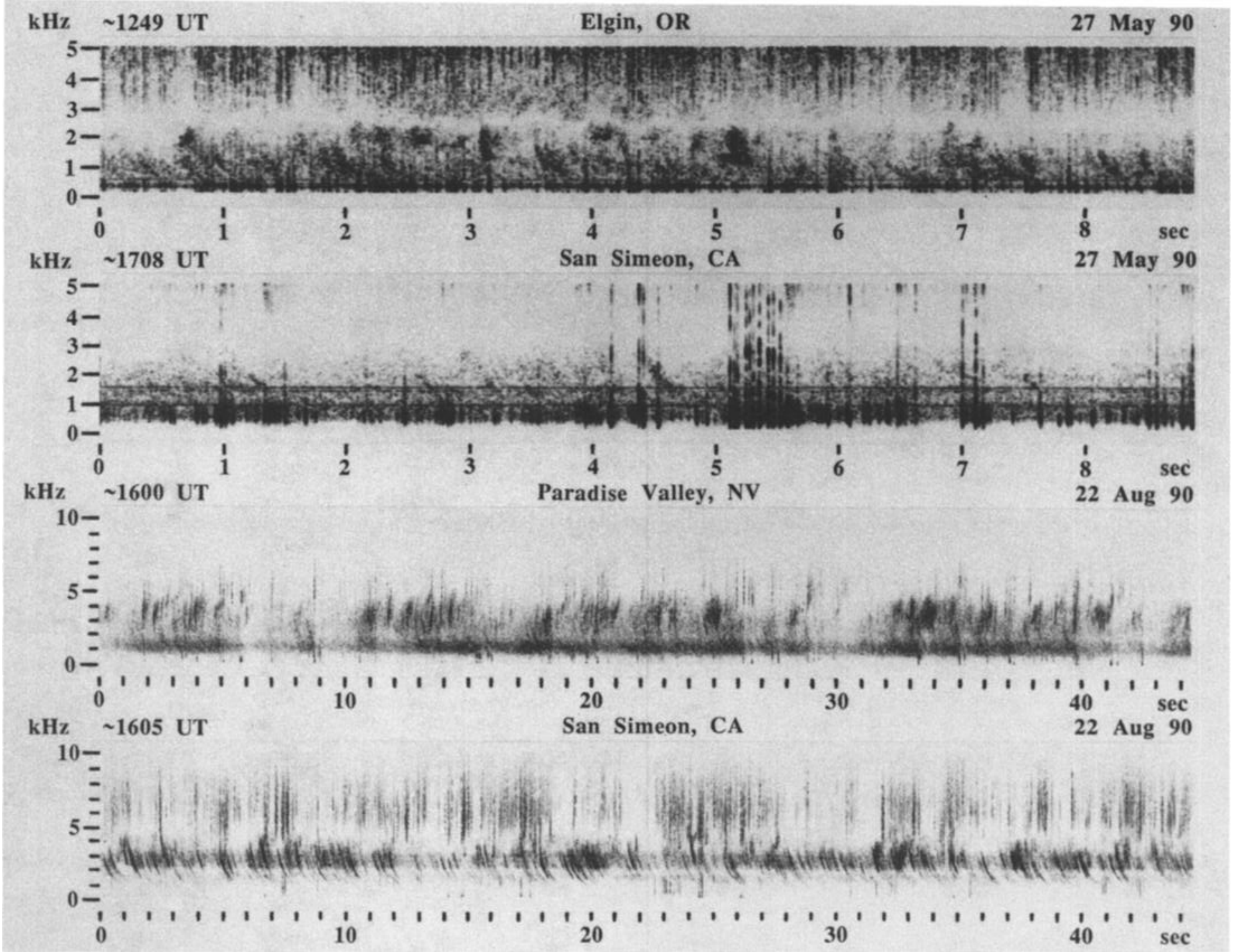
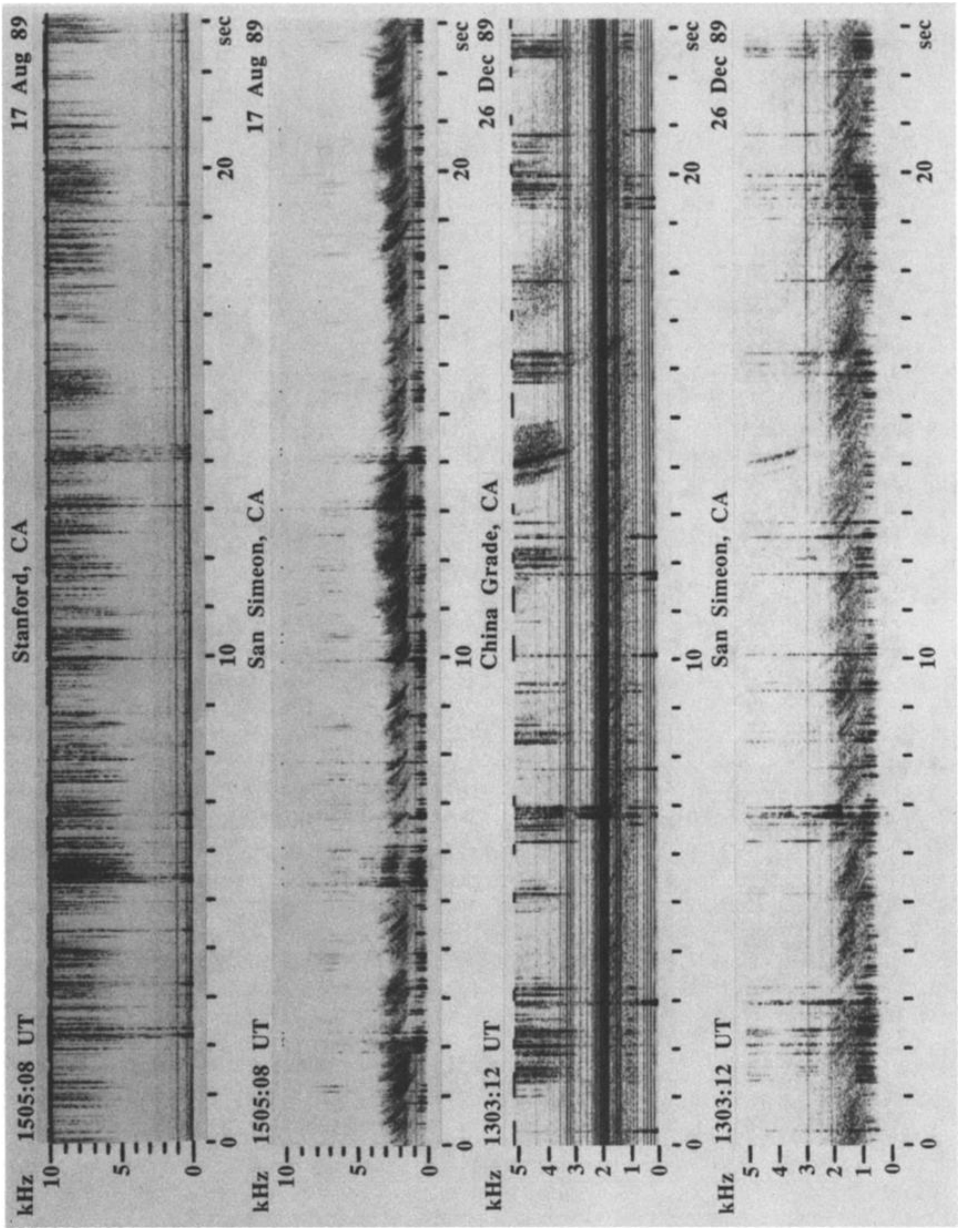


Figure 10. Observations at widely separated sites. (upper two panels) "Whistler storm" seen at Elgin, Oregon, May 27, 1990 ≈1249 UT by Steve Ratzlaff and possibly the same "whistler storm" seen May 27, 1990 ≈1708 UT at San Simeon, California. (lower two panels) "Whistler storm" seen at Paradise Valley, Nevada, August 22, 1990 ≈1600 UT by Steve McGreevy and presumably the same "whistler storm" seen August 22, 1990 ≈1605 UT at San Simeon, California. Distances between recording sites are ≈ 1000 km. "Whistler storms" are visible over a broad area, which is consistent with the hypothesis that TEM propagation of whistlers is the cause.


kHz
1505:08 UT
Stanford, CA
17 Aug 89
10
5
0
0
10
20
sec
kHz
1505:08 UT
San Simeon, CA
17 Aug 89
10
5
0
0
10
20
sec
kHz
1303:12 UT
China Grade, CA
26 Dec 89
5
4
3
2
1
0
0
10
20
sec
kHz
1303:12 UT
San Simeon, CA
26 Dec 89
5
4
3
2
1
0
0
10
20
sec

70 km and ground conductivity of 3.5×10^{-6} S/m determined from the August 17, 1989, case, equation (3) yields a propagation distance of 2600 km. The increase to 2600 km for the 1.5 kHz center frequency versus 2000 km for the 2.5 kHz center frequency case seems reasonable for whistler sources displaced longitudinally from the nearest point on the L=5 contour of Figure 1. Scaling of six elements from the December 26, 1989, "whistler storm" yielded one element each at L=2 and L=4, and four elements between L=4.5 and L=5.5.

Sferics also contribute to VLF noise below 5 kHz. Figure 12 shows spectrograms of data from South Pole on December 26, 1989. In the upper panel (0 - 11 kHz) and the middle panel (0 - 5 kHz), the presence of noise below 1 kHz is clear, but only in the lower panel (0 - 1.5 kHz) is it clear that this narrowband noise is due to sferics. The upper panel is at a different timescale than the middle and lower panels, and also was processed so that the grey scale saturates at a lower signal intensity than in the middle and lower panels. This was done in order to show the sferics above 5 kHz more clearly. The "sferic storm" band lies near 400 Hz. Assuming daytime conditions (Antarctic summer), and that ice and dry rock are comparable insulators, equation (3) yields a propagation path length of about 2600 km (about 24 degrees of latitude). This correlates remarkably well with the fact that most of the Antarctic coastline lies between 70 and 65 degrees south latitude. While there are no lightning centers off the Antarctic coast, on a mixed sea and ice path the attenuation effects of the ice portion of the path would dominate, producing such a narrowband VLF signal as is observed. Some wider-band "pieces of sferics", such as that at 10.5 s in the middle panel, can also be seen. A similar calculation, taking the center frequency of these as $\approx$ 1 kHz with all other parameters unchanged, yields a propagation path length of $\approx$ 1700 km, about the distance from the South Pole to the Amundsen Sea coast (near SI in Figure 1).

Conclusion

Unusual narrowband noise below 5 kHz, dubbed "whistler storms", can be explained by propagation in the Earth-ionosphere waveguide from known natural sources. Tests of this hypothesis show that the properties expected from long distance propagation in the quasi-TEM mode, specifically a filtering effect which reduces the spectral bandwidth and decreases the band center frequency as distance to the source increases, match those of observed signals. In addition, "whistler storm" elements have curvatures consistent with whistlers at large distances from receiving sites as sources, and "whistler storms" tend to occur under geomagnetic conditions which are known to favor whistler occurrence. Diurnal variations in the Earth-ionosphere waveguide height can account for the tendency of "whistler storms" to commence near local dawn, as well as correlation of "whistler storms" with low atmospheric noise levels. Previous recognition of this phenomenon may have been hindered by interference from power line harmonics at urban sites, and by spectral processing of broadband data from quiet sites which was optimized for presentation of higher frequency, wider bandwidth signals such as whistlers. Such processing tends to obscure "whistler storms" and related phenomena. Other examples of such VLF noise may be available in various data archives. The Antarctic data presented here were unearthed only after the San Simeon "whistler storm" data motivated a search for narrowband VLF noise.

Figure 11. Site comparison. (upper two panels) Stanford noise survey and San Simeon broadband data of August 17, 1989, 1505:08–1505:29 UT. Due to strong power line hum at its urban site, the Stanford data show no hint of the "whistler storm". The San Simeon data show an intense "whistler storm", also sferics which line up with sferics on the Stanford data. (The rolloff above 7 kHz in the San Simeon data is due to receiver filtering.) (lower two panels) China Grade and San Simeon broadband data of December 26, 1989, 1303:12–1303:35 UT. Both are rural sites, but the China Grade site is considerably more accessible. Power line hum obscures all but the strongest "whistler storm" elements in the China Grade data. The San Simeon data show a clearly visible "whistler storm", also sferics which line up with sferics on the China Grade data. A sensitive receiver at a quiet (isolated?) site is required to observe these events.

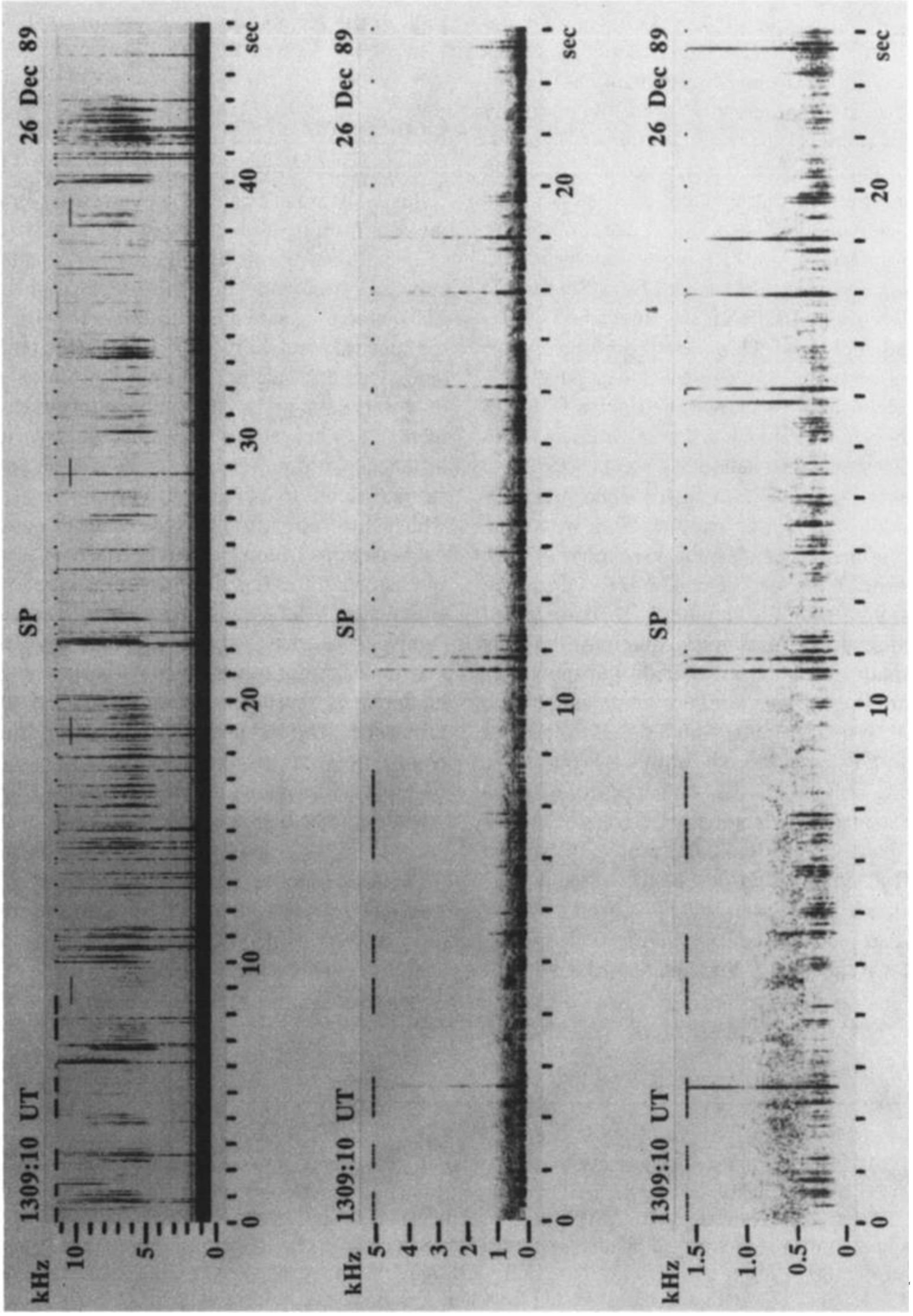

kHz
10
5
0
1309:10 UT
SP
26 Dec 89
0
10
20
30
40
sec
kHz
5
4
3
2
1
0
1309:10 UT
SP
26 Dec 89
0
10
20
sec
kHz
1.5
1.0
0.5
0
1309:10 UT
SP
26 Dec 89
0
10
20
sec

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Figure 12. Quasi-TEM mode propagation. (top) December 26, 1989, 1309:10 UT wideband (0–11 kHz) data from South Pole. The high frequency sferic cutoff (above 10 kHz) is due to filtering to reduce OMEGA navigation signals. The low frequency sferic cutoff (below 5 kHz) is due to increased TE and TM attenuation near the $\approx$ 2 kHz cutoff frequency. Some sferics are visible below 5 kHz; these are presumably TEM mode signals. Given the Antarctic climate, they are certainly not nearby lightning. Grey scale saturation of strong signals in this spectral display makes it difficult to estimate intensity versus frequency below 5 kHz in this panel. Due to saturation and "blooming" effects in the spectral processing, structure in the very strong band below 1.5 kHz is not visible. At this spectrogram scale and gain setting, typically used for data surveys, the quasi-TEM mode propagation below 1 kHz is unlikely to attract attention, and might be mistaken for power line harmonics. (middle) December 26, 1989, 1309:10 UT medium band (0–5 kHz) data from South Pole. The quasi-TEM mode propagation is visible though ill defined. Gain in the spectral processing was reduced, and the time base was increased. Only the strongest signals in the 1–5 kHz range, such as that at 10.5 s, are still visible. A reduction in intensity (darkness) with increasing frequency is visible on that element, as might be expected for quasi-TEM propagation. (bottom) December 26, 1989, 1309:10 UT narrowband (0–1.5 kHz) data from South Pole. Gain is further reduced. The quasi-TEM mode propagation below 1 kHz is now well defined, with numerous short "pieces of sferics" visible. Bandwidths and center frequencies of elements below 5 kHz in this figure are consistent with reasonable propagation paths over the Antarctic continent. It is probable that careful examination of archived data would show many such examples.

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