RECEPTION OF ELF SIGNALS AT ANTIPODAL DISTANCES

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Abstract

Measurements of 82 Hz radio signals from a Russian ELF transmitter located on the Kola Peninsula are described. The measurements were made at several locations around the world, including Dunedin, New Zealand, and Arrival Heights, Antarctica, which are close to the antipodal point for the transmitter. This is the first time man-made ELF signals have been observed over such long distances and their clear reception makes possible a comparison of the theoretically predicted and measured amplitudes near the antipode. The agreement is excellent.

Introduction

During January 1990, CW radio transmissions at a frequency of 82 Hz were successfully received for many days at a number of the combined extremely-low and very-low frequency (ELF/VLF; frequencies in the range 5 Hz – 30 kHz) radio noise measurement systems operated around the world by Stanford University [*Fraser-Smith et al.*, 1985, 1988; *Füllekrug and Fraser-Smith*, 1996]. Specifically, the transmissions were observed at Søndrestrømfjord, Greenland (67° N, 51° W), Kochi, Japan (33° N, 227° W), Dunedin, New Zealand (46° S, 170° E), and Arrival Heights, Antarctica (78° S, 167° E); they could not be detected above the normal background noise at the Stanford University site in California (37° N, 122° W).

At the time of measurement of these ELF signals there was no available description of any ELF transmitting system operating at 82 Hz. This was surprising, since ELF transmitters for global communications are expensive to build and to operate and, by contrast, there was an extensive literature covering the development and deployment of the United States'

WTF/MTF (Wisconsin Transmitter Facility/Michigan Transmitter Facility) dual antenna transmitting system, which typically operates at a center frequency of 76 Hz. Guided, however, by the comparatively large 82 Hz signal strength at Søndrestrømfjord, and by the references to a Russian ELF transmitter in a novel by Tom Clancy [*Clancy*, 1990], who has a reputation for accuracy in regard to defense matters, we provisionally assumed that the source of the 82 Hz signals was in Russia, and that it was most probably located on the Kola Peninsula, which has the necessary very low electrical conductivity for operation of a ground-based ELF transmitter [*Vagin et al.*, 1985]. The lack of detectable signals at Stanford, and some other details of the signal strengths, combined with practical considerations, suggested that the antenna was a long horizontal electric dipole (HED) antenna oriented in an approximate east-west (EW) direction.

We have since confirmed, from Russian sources [E. Tereshchenko, personal communication, 1996; *Velikhov et al.*, 1996], that there is indeed a Russian ELF transmitter located on the Kola Peninsula, at a location (69° N, 33° E) near Murmansk in the northwest of the peninsula. As described by *Velikhov et al.*, [1996], "the transmitter consists of two swept-frequency generators of sinusoidal voltage and two parallel horizontal grounded antennas, each about 60 km long. The generators provide 200 to 300 A currents in the antennas in the frequency range from 20 to 250 Hz." In the following, we will assume that the Russian ELF transmitter (hereafter referred to as the Kola Peninsula Transmitter Facility, or KPTF) is located on the Kola Peninsula at 69° N, 33° E, and that the azimuthal orientation (taken to be $\phi = 0°$) of the long HED (or equivalent horizontal magnetic dipole (HMD) [*Bannister*, 1966]) is approximately 13° N of E (77° E of N). The antipodal point for the KPTF is at 69° S, 213° E, which is located off the coast of the Antarctic in the north-eastern part of the Ross Sea, near Marie Byrd Land, and the great circle distances of this antipodal point from the Arrival Heights and Dunedin measurement sites are 1.7 Mm and 3.5 Mm, respectively.

It is remarkable to have measurements of man-made ELF signals over such long ranges, and particularly at antipodal distances (where a form of focusing of the signals is predicted theoretically), and they provide a unique opportunity to test the propagation theory for these ELF signals at large distances from their source for the first time. The purpose of this paper is to describe our comparison of the measured and theoretically-expected signal amplitudes and to show the excellent agreement between the two quantities.

Analysis of the Measurements

The great circle distance (ρ) from KPTF to Søndrestrømfjord is close to 3.2 Mm, which, to two significant figure accuracy, is the same as the distance from the WTF/MTF combination to Søndrestrømfjord. Given this fortuitously close agreement in range, it is significant that our measurements indicate that the normalized (to $\phi = 0°$) 82 Hz Søndrestrømfjord field strength is 10 dB greater than the 76 Hz Søndrestrømfjord WTF/MTF field strength. A similar 10 dB difference is also obtained when appropriate comparison is made between the 82 Hz field strength for the KPTF-to-Japan path (7.0 Mm) and the 76 Hz field strength for the WTF/MTF-to-Hawaii path (6.7 Mm). We will therefore assume that the 82 Hz KPTF magnetic dipole moment (M) is 10 dB greater than the 76 Hz combined WTF/MTF magnetic dipole moment.

For an HMD antenna

$$M = ILW \tag{1}$$

where M is the magnetic moment (Am^2), L is the antenna length (m), I is the antenna current (A), and where W (m) is the effective vertical extent, or depth, of the antenna. For a single layer earth, with an electrical conductivity of σ_1 and magnetic permeability μ_0, W is given by

$$W \approx \frac{1}{|\gamma_1|} = \frac{\delta_1}{\sqrt{2}} \tag{2}$$

where γ_1 is the propagation constant and $\delta_1 = (2/\omega\sigma_1\mu_0)^{1/2}$ is the corresponding skin depth [*Bannister*, 1966]. If we assume there is a second layer of conductivity σ_2 starting at a depth of h_1 beneath the first, and that $\sigma_1 \ll \sigma_2$ and $\tanh \gamma_1 h_1 \sim \gamma_1 h_1$, we have

$$W \approx h_1 \tag{3}$$

The average effective conductivity of the earth beneath the WTF/MTF antennas is approximately 2.4×10^{-4} S/m [*Bannister*, 1976; *Wolkoff and Kraimer*, 1993], which gives an effective depth of $W \sim 2.6$ km at a frequency of 76 Hz. For the very low conductivity

Kola Peninsula area, there is a first layer with a conductivity of approximately 10^{-5} S/m down to a depth (h_1) of approximately 10 km, beneath which there is a second layer with a conductivity of approximately 10^{-3} S/m [*Vagin et al.*, 1985]. Thus condition (3) applies and $W \sim 10$ km, which is approximately four times greater than the value of W for the WTF/MTF antenna combination.

For the combined WTF/MTF antennas, operating at 76 Hz, we have

$$M \approx 2 \times 300\,(\mathrm{A}) \times 22.5\,(\mathrm{km}) \times 2.6\,(\mathrm{km}) = 3.51 \times 10^4\,(\mathrm{A\,km^2}) \tag{4}$$

Since the magnetic moment for the KPTF is approximately 10 dB greater than that of the WTF/MTF combination, it must equal 1.1×10^5 $\mathrm{A\,km^2}$. For an antenna length of 55 km, the required current I is 200 A. That is, at 82 Hz:

$$M \approx 200\,(\mathrm{A}) \times 55\,(\mathrm{km}) \times 10\,(\mathrm{km}) = 1.1 \times 10^5\,(\mathrm{A\,km^2}) \tag{5}$$

Figure 1 shows a plot of the variation with frequency (in the range 0–400 Hz) of the measured ELF magnetic field strength at Søndrestrømfjord for January 1990, during the times when the 82 Hz signal was present. The effective integration time is 1185 minutes (the number of the 2 one-minute samples/hour recorded during January that contained 82 Hz transmissions). The total number of possible one-minute samples is 1488, so transmissions were detected 80% of the time. The plot clearly shows the first seven Schumann resonances, the 50 and 60 Hz power line frequencies (and their related harmonics), and the spectral peak corresponding to the 82 Hz transmissions.

The January 1990 82 Hz field strengths measured at Søndrestrømfjord, Dunedin, and Arrival Heights (and estimated at Stanford) are presented in Table 1. Also listed are the 1985–1994 January 80 Hz median atmospheric noise values measured in dBH_T (H_T is the total horizontal magnetic field noise level; the unit of H_T is dB with respect to the reference quantity of one ampere per meter in a 1 Hz bandwidth), and the signal-to-noise ratios (SNR's) for both a 1 Hz bandwidth (BW) and for a 2 minute integration time (IT). Note that the measured Søndrestrømfjord 2–minute integration time SNR is 25 dB, which corresponds to an easily measured signal. On the other hand, the estimated Stanford 2–minute integration time SNR is ≤ 1.5 dB, which is undetectable.

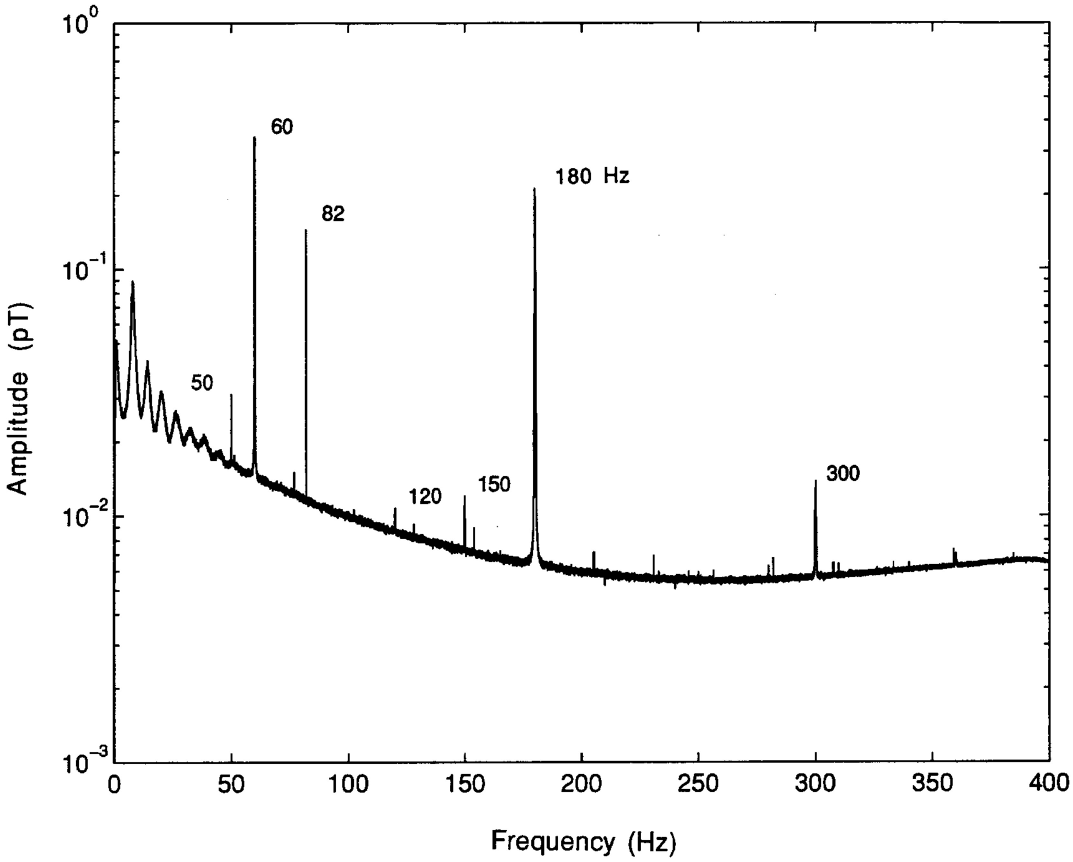

Figure 1. Average amplitude spectrum of the lower-ELF radio noise at Søndrestrømfjord, Greenland, during January, 1990. The average spectrum is computed from the 1185 one-minute synoptic recordings taken twice per hour that contained 82 Hz transmissions; the overall total possible number of these one-minute recordings during January is 1488.

The receiving antennas at the Stanford University ELF/VLF measurement locations are normally installed as perpendicular pairs, with one antenna oriented in the magnetic NS direction and the other otherwise identical antenna oriented in the magnetic EW direction, and it is the signals received on the magnetic NS aligned antennas that were employed in this analysis. Since the magnetic NS direction is different from the great circle path direction from KPTF to these sites, a receiving antenna correction factor must be employed. The correction factors varied from 0 dB at Søndrestrømfjord to 6.5 dB at Arrival Heights. Also, since these sites are off axis to the KPTF antenna (i.e., $\phi \neq 0°$), a transmitting antenna correction factor must also be employed. These transmitting antenna correction factors vary from 2.0 dB at Dunedin to 8.6 dB at Arrival Heights.

TABLE 1

The 82 Hz field strengths measured at Søndrestrømfjord, Dunedin, and Arrival Heights during January 1990. The estimated field strength at Stanford is also shown.

Location	KPFT Range (Mm)	Median Noise Jan 80 Hz (dBH_T)	Measured H_ϕ (dBA/m)	SNR 1 Hz BW (dB)	SNR 2 min. IT (dB)
Søndrestrømfjord	3.2	−139.7	−135.6	+4.1	24.9
Dunedin	16.5	−134.7	−142.5	−7.8	13.0
Arrival Heights	18.3	−140.5	−151.9	−11.4	9.4
Stanford	8.1	−136.4	≤ -155.7*	≤ -19.3*	≤ 1.5*

*estimated

Presented in Table 2 are the measured and normalized (to $\phi = 0°$) field strengths at each of the three sites. From this table, we see that the normalized 82 Hz field strengths are −131.8, −139.0, and −136.8 dBA/m, at Søndrestrømfjord, Dunedin, and Arrival Heights, respectively.

TABLE 2

Measured and normalized (to $\phi = 0°$) field strengths at the three Stanford measurement sites. The receiving antenna (RA) and transmitting antenna (TA) correction factors are listed for each site.

Location	Measured H_ϕ (pT)	Measured H_ϕ (dBA/m)	KPFT Range (Mm)	Correction Factor, RA (dB)	Correction Factor, TA (dB)	H_ϕ ($\phi = 0°$) (dBA/m)
Søndrestrømfjord	0.208	−135.6	3.2	0.0	3.8	−131.8
Dunedin	0.0943	−142.5	16.5	1.5	2.0	−139.0
Arrival Heights	0.0319	−151.9	18.3	6.5	8.6	−136.8

Following *Bannister* [1975, 1993, 1996], the 76 Hz magnetic field strength produced at distances in the range 1 to 19 Mm by the WTF/MTF combination in an omnidirectional mode (i.e., independent of ϕ) may be expressed as

$$20\ \log H_\phi \approx -131.8 + 20\ \log E - \alpha\,\rho - 10\ \log(a \sin \rho/a) \quad \text{dbA/m} \tag{6}$$

where E is the excitation factor, α is the attenuation rate (measured in dB/Mm), ρ is the great circle distance (measured in Mm), and a is the radius of the earth (6.370 Mm). E is defined as:

$$E = \frac{55.90}{h\sqrt{c/v}} \quad \text{km}^{-1} \tag{7}$$

where h is the ionospheric reflection height in km, and c/v is the earth-ionosphere waveguide phase velocity ratio.

We have shown that the 82 Hz KPTF field strength is 10 dB greater than that of the 76 Hz WTF/MTF combination in an omnidirectional mode. As a result, the 82 Hz magnetic field strength produced by the KPTF for distances in the range 1 to 19 Mm may be expressed as

$$20 \log H_\phi \approx -121.8 + 20 \log E - \alpha\rho - 10 \log(a \sin \rho/a) + 20 \log \cos \phi \quad \text{dBA/m} \tag{8}$$

At the antipode ($\rho = 20$ Mm), the spreading loss factor ($-10\log(a\sin\rho/a)$) is replaced by $+10\log(\pi^2(c/v)/\lambda)$ [*Galejs*, 1972; *Burrows*, 1978], where λ is the free space wavelength in Mm. For frequencies of 76 to 82 Hz and $c/v \sim 1.09$ (nighttime propagation), the antipodal spreading loss (which is actually a focusing gain) varies in the range +4.3 to +4.7 dB.

Utilizing eqn (8) and comparing the Søndrestrømfjord/Dunedin and Søndrestrømfjord/Arrival Heights field strengths (Table 2) results in an attenuation rate of 0.5 dB/Mm and excitation factor of 0.65 (−3.7 dB) for the KPTF signals. These are clearly nighttime values of α and E, since typical daytime values of α and E are 1.3 dB/Mm and 0.91 (−0.8 dB), respectively [*Bannister*, 1993, 1996].

This comparison indicates that the nighttime 82 Hz field strengths at antipodal distances (15 to 20 Mm) will be substantially greater than the daytime field strengths. For example, at a range of 17.5 Mm, the nighttime field strength will be $(17.5(1.3-0.5)-3.7+0.8) = 11.1$ dB greater than the daytime field strength.

The average 76 Hz nighttime attenuation rate (α_N) measured over various paths (with lengths in the range 1.5 to 11.5 Mm) is ~ 1.0 dB/Mm [*Bannister*, 1985, 1993, 1996]. However, during January, $\alpha_N \sim 0.6$ dB/Mm for the WTF/MTF to Hawaii path. Because of the effect of earth's magnetic field, we would expect the attenuation rate for this predominantly EW path to be greater than the attenuation in the WE or NS directions (such as KPTF–to–Dunedin and KPTF–to–Arrival Heights paths). Thus, a nighttime attenuation rate value of 0.5 dB/Mm is reasonable for the given time of year. (An exponential ionospheric conductivity profile with $\beta = 0.55$ km^{-1} and $H = 95$ km, as was used by *Wait and Spies* [1964], yields $\alpha \sim 0.5$ dB/Mm). On the other hand, if the measurements were taken in the March/April time period, the nighttime attenuation rate would be ~ 1 dB/Mm [*Bannister*, 1993, 1997].

Shown in Figure 2 are the predicted KPTF 82 Hz field strengths versus range for both all-daytime and all-nighttime propagation paths. The azimuthal angle ϕ is assumed to be 0°. The nighttime and daytime attenuation rates are assumed to be 0.5 and 1.3 dB/Mm, respectively, while the nighttime and daytime values of E are assumed to be −3.7 dB and −0.8 dB, respectively. Also plotted in the figure are the normalized (to $\phi = 0°$) Søndrestrømfjord, Dunedin, and Arrival Heights measured field strengths. Note the excellent agreement between the predicted and measured values at all three sites. For further comparison, we have

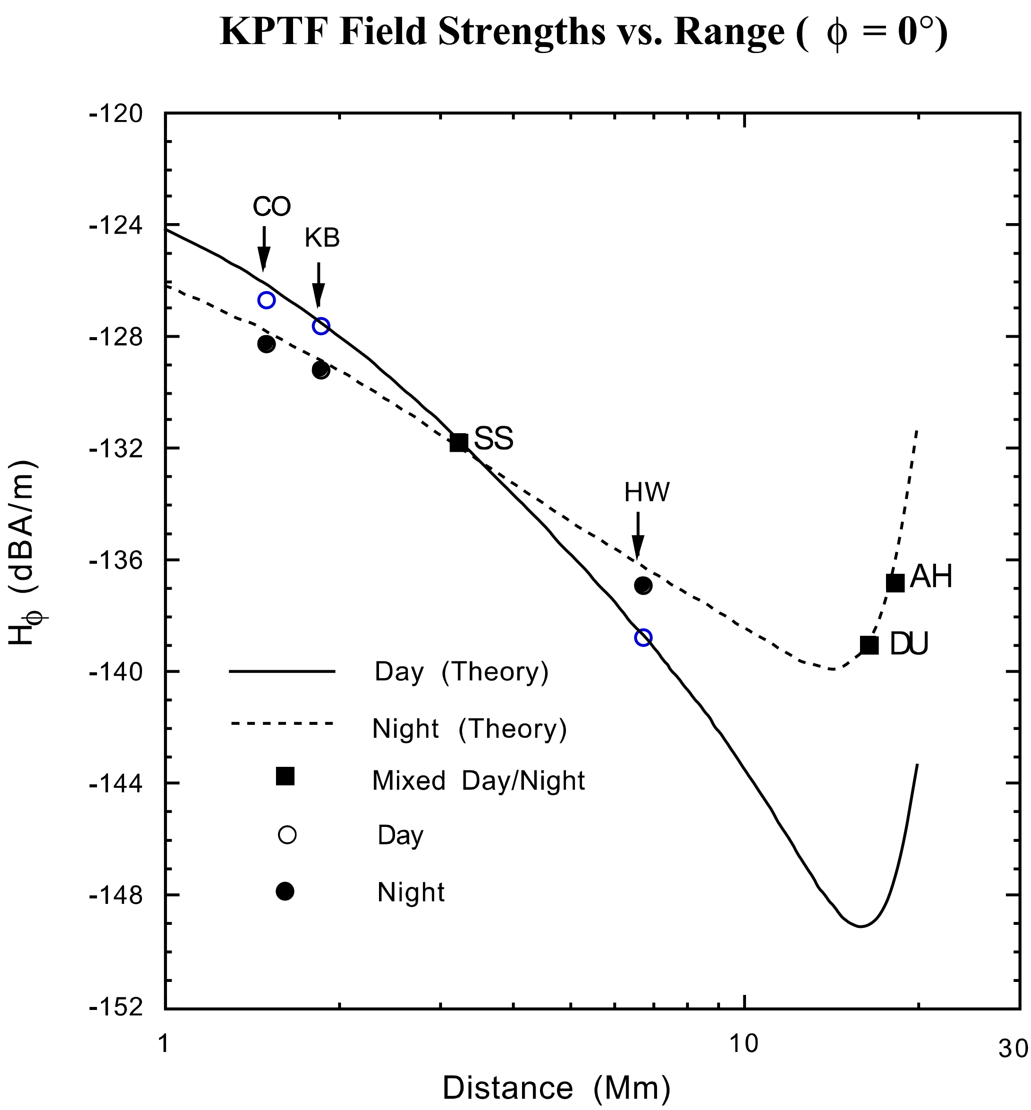

Figure 2. Curves showing measured and predicted values of the KPTF 82 Hz field strengths. The two curves show theoretically-predicted values for all-day and all-night paths over global ranges and the measured field strengths at Søndrestrømfjord (SS), Dunedin (DU), and Arrival Heights (AH) are shown as three labelled points. January WTF/MTF 76 Hz field strengths in Connecticut (CO), Hawaii (HW), and at King's Bay, Georgia (KB) are also shown for comparison.

also plotted the 76 Hz field strengths for January as measured in Connecticut, King's Bay (Georgia), and Hawaii [*Bannister*, 1997]. 10 dB has been added to the measured values to adjust for the difference in transmitter strengths and the distances are measured from the WTF/MTF midpoint. Again, the agreement is excellent. (The Hawaii measured nighttime field strength is 0.7 dB low, but this is because the nighttime attenuation rate in this EW direction is 0.1 dB/Mm greater than in the WE/NS directions).

Field strengths of the 82 Hz signal for mixed day/night paths were also measured at Kochi, Japan (7 Mm range) during January through March, 1990. As we have already noted, the normalized field strengths were almost identical to the 76 Hz field strengths (with 10 dB added) for the Hawaii mixed day/night path (6.7 Mm range) for the same three month interval.

Conclusion

During January 1990, 82 Hz CW transmissions were successfully received for many days at a number of ELF/VLF radio noise measurement sites operated by Stanford University around the world. The source of these transmissions was undoubtedly the Russian ELF transmitter (KPTF) located in the Kola Peninsula, which is about 10 dB more powerful than the U.S. 76 Hz dual transmitting system (WTF/MTF).

It is particularly interesting that the 82 Hz signals could be clearly measured at Dunedin, New Zealand, and Arrival Heights, Antarctica, which are close to the antipodal point of the KPTF. This is the first time that man-made ELF signals have been received over such long distances. Reception of the signals made possible a comparison of the theoretically-expected and measured signal amplitudes near the antipode and the agreement is excellent, as it is at all of the measurement sites.

Additional comparison of the 82 Hz KPTF and 76 Hz WTF/MTF signal strengths (with the 76 Hz strengths adjusted to compensate for their 10 dB weaker transmitter) measured at different sites and times yields almost identical values of ELF attenuation rates and excitation factors.

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References

Bannister, P. R., "Quasi-static fields of dipole antennas at the earth's surface," *Radio Science, 1*, 1321–1330, 1966.

Bannister, P. R., "Variations in extremely low frequency propagation parameters," *J. Atmos. Terr. Phys., 37*, 1203–1210, 1975.

Bannister, P. R., "Summary of the Wisconsin Test Facility effective earth conductivity measurements," *Radio Sci., 11*, 405–411, 1976.

Bannister, P. R., "The determination of representative ionospheric conductivity parameters for ELF propagation in the earth-ionosphere waveguide," *Radio Sci., 20*, 977–984, 1985.

Bannister, P. R., "ELF propagation highlights," *AGARD Conference Proceedings 529*, 2-1–2-15, 1993.

Bannister, P. R., "Further examples of seasonal variations of ELF propagation parameters," (in preparation), 1997.

Burrows, M. L., *ELF Communications Antennas*, Peter Peregrinus, Stevenage, England, 1978.

Clancy, T., *The Hunt for Red October*, Berkley Books, N.Y., 1990.

Fraser-Smith, A. C., and R. A. Helliwell, "The Stanford University ELF/VLF radiometer project: Measurement of the global distribution of ELF/VLF electromagnetic noise," *Proc. 1985 IEEE Internat. Symp. on Electromag. Compatability, IEEE Catalog No. 85CH2116–2*, 305–311, August 1985.

Fraser-Smith, A. C., R. A. Helliwell, B. R. Fortnam, P. R. McGill, and C. C. Teague, "A New Global Survey of ELF/VLF Radio Noise," Conf. on Effects of Electromagnetic Noise and

Interference on Performance of Military Radio Communication Systems, Lisbon, Portugal, 26–30 October, 1987, published in *AGARD Conference Proceedings No. 420*, pp. 4A-1–4A-9, December 1988.

Füllekrug, M., and A. C. Fraser-Smith, "Further evidence for a global correlation of the Earth-ionosphere cavity resonances," *Geophys. Res. Letts., 23*, 2773–2776, 1996.

Galejs, J., *Terrestrial Propagation of Long Electromagnetic Waves*, Pergamon Press, N.Y., 1972.

Vagin, S. A., Vardanyants, I. L., A. A. Kovtun, E. L. Kokvina, O. N. Moiseyev, A. A. Savel'yev, and N. I. Uspenskiy, "Magnetotelluric sounding in the 10^{-3} to 10^{4} second period interval in the Murmansk block of the Kola Peninsula and in Central Karelia," *Izvestia, Earth Physics, 21*, 444–450, 1985.

Velikhov, E. P., A. A. Zhamaletdinov, L. A. Sobchakov, A. V. Veshev, A. K. Sarayev, A. D. Tokarev, A. N. Shevtsov, A. V. Vasil'yev, A. G. Sonnikov, and A. V. Yakovlev, "Extra-low frequency sounding of the Earth's crust with a high-power antenna," *Trans. Russian Acad. Sciences (Doklady), 341*, 12–16, 1996.

Wait, J. R., and K. P. Spies, "Characteristics of the earth–ionosphere waveguide for VLF radio waves," *NBS Tech. Note 300*, 1964.

Wolkoff, E. A., and W. A. Kraimer, "Pattern measurements of U.S. Navy ELF transmitters," *AGARD Conf. Proc., 529*, 26-1–26-10, 1993.