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The Northwest Passage Propagation Experiment: Report of the 1983-1984 Measurement Program

by
R.S. Butler

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ABSTRACT

An experiment was undertaken in 1982 to study radio propagation conditions in the VHF and UHF bands in the Canadian Arctic Islands near latitude 75°N. There were five UHF paths having both ends elevated to study point-to-point relay links. At VHF there were nine paths from near sea level to sites at various elevations to study links from ship to shore. Path lengths were in the range 60 to 100 km and were representative of the paths needed for a maritime mobile communication system to cover the entire Northwest Passage.

This report covers the measurements made between September 1983, and January 1985. Annual, seasonal, and worst-month statistics are presented and analyzed. It is concluded that reliable VHF communications can be provided to ships in the Northwest Passage using modest transmitter powers (less than 3 watts per 25 kHz voice channel), while very low transmitter powers (less than 0.1 watts per channel) would be adequate for UHF relay links between VHF sites.

1. INTRODUCTION

The portion of Canada north of the Arctic Circle includes an extensive group of islands, covering an area of about 2 million km^2 and extending to latitude 80°N. The Northwest Passage, the fabled northern sea route through the Americas from Europe to the Orient, passes through this archipelago near latitude 74°N between Baffin Bay on the east and the Beaufort Sea on the west.

Communications in this very sparsely populated region have traditionally used HF radio, supplemented by troposcatter systems farther south, and more recently by microwave links through geostationary satellites. However, the possibility of increased marine traffic because of natural resource development has led to the investigation of a VHF mobile radio system, and this has required a study of radio propagation in this unique Arctic region. A preliminary investigation (Dubinski, 1982) of probable shore sites for optimum coverage of the entire Passage was used to guide the choice of links for this study, as summarized in section 5.2, below. The experimental VHF frequencies were chosen within the maritime mobile frequency band, 156 to 174 MHz, and VHF links were chosen up to a maximum distance of 95 km between simulated shipboard locations and an elevated site. As well, UHF paths were investigated in the 450 to 470 MHz band, with lengths up to 100 km between elevated points. The purpose of the experiment at both VHF and UHF is to examine the range of path lengths needed to cover the whole Northwest Passage from longitude 80°W to 125°W, and to deduce parameters for a highly reliable communications system.

The initial phase of the experiment was conducted in 1982, and the results obtained have been reported by Butler, et al. (1984). The measurement program was continued throughout 1983 and 1984, and the results obtained during this period are analyzed in the present report.

2. GEOGRAPHY AND CLIMATE

The geographical location of the experimental area is shown in Figure 1. Figure 2 is a detailed map of the area, with the experimental links indicated. Near Cape Cockburn there are three independent sites, Cockburn Peak, Cockburn Lake, and Cockburn Flats, at different elevations along almost the same line to Lowther Island. There are also three sites on Lowther Island at different elevations along almost the same line from Cape Cockburn, namely Lowther Beach, Lowther Terrace, and Lowther Peak. These six sites cannot be shown separately on the scale of Figure 2. Unofficial names and locations of all sites are given in Table 1, together with the approximate frequency of transmission from each site.

Table 1 Experimental Site Details

Site Name	Latitude	Longitude	Elevation (m)	Frequency (MHz)
Transfer Hill	75° 35.3'N	105° 35.1'W	140	451.0
Schomberg Peak	75° 33.7'	102° 41.1'	177	463.0
Cockburn Peak	75° 01.8'	100° 15.1'	156	453.0
Cockburn Lake	75° 01.6'	100° 10.0'	80	458.0
Cockburn Flats	75° 00.2'	100° 05.9'	11	164.0
Allison Inlet	74° 59.9'	99° 31.2'	16	164.4
Acland Acres	75° 00.0'	98° 51.0'	15	165.0
Lowther Beach	74° 33.4'	97° 36.0'	15	72.1
Lowther Terrace	74° 32.6'	97° 33.0'	100	72.6
Lowther Peak	74° 31.8'	97° 27.2'	183	468.0
Martyr Peak	74° 41.2'	95° 02.9'	174	165.3

The entire area of Figure 2 lies within the climatic sub-region Ic: Bathurst Island - Prince of Wales Island as defined by Maxwell (1981). The climate is an Arctic desert type, with less than 15 cm of annual water equivalent precipitation, mostly as snow. The mean daily temperature is +4°C in July and -33°C in January. Fog or ice fog occur about 15% of the time in the months June to August, and 10% in the months December to February. Low cloud is prevalent for much of the year, with ceilings below 300 metres for 28% of the time in the months June to August.

The sea channels are covered with ice for 9 to 12 months of the year, with open water being least frequent north of Byam Martin Island and most frequent along the south coast of Bathurst and Cornwallis Islands. Most of the spring ice is less than one year old, and thicknesses are typically two metres. The main period of open water usually occurs in August (Rae, 1951).

The unbroken winter night at latitude 75°N lasts from November 3 to February 9, and the unbroken summer day from May 1 to August 13, while the length of the day changes from 0 to 24 hours, and back, around the spring and autumn equinoxes. In winter widespread thermal inversions occur 80% of the time because of radiative cooling of the surface, and even in the period June to August the atmosphere remains largely non-convective over the nearly isothermal surface of ice and sea water, so that thermal inversions occur for 40% of the time.

The monthly mean and 95% probability limits of the atmospheric refractivity at Resolute are shown in Figure 3 as the shaded band. The line connecting the open circles is the mean dry air component of the refractivity, so that the contribution from water vapour is the difference between this line and the overall mean line which connects the filled circles. The reduction of both the refractivity and the range of refractivity during the months May to September is characteristic of the Arctic Islands and the reverse of what is observed in temperate latitudes. This figure and Figure 4, below, are reproduced with the permission of Dr. B. Segal from Segal and Barrington (1977).

The seasonal probability distributions of the ground-based refractivity gradient for Resolute are shown in Figure 4, for the lower 100 metres of the atmosphere. Since the elevation of the upper air station is 64 m, the gradients refer to the altitude range 64 to 164 m. The right-hand scale of the figure shows the effective earth radius factor, k_e, corresponding to the left-hand refractivity gradient scale. An effective earth radius of 4R/3 (where R is true earth radius, 6365 km), which is near the median value in temperate regions, is clearly smaller than the median here except in summer. This means that the path profiles calculated on a 4R/3 effective earth radius basis, and shown later, exaggerate the bulge of the earth into the radio paths. In winter the earth appears even flatter for large fractions of the time ($>$ 25% for $k_e \geq 2$), and ducting (k_e negative) is not extremely rare. Conversely, the occurrence of small values of k_e (<1) is rare, except perhaps in summer so that "earth bulging", the blocking of radio paths by increased bending of the rays to intersect the surface, is not expected to be common.

3. EXPERIMENTAL DETAILS

A block diagram of the flow of RF signals is shown in Figure 5. The signal level received from Transfer Hill was measured at Schomberg Peak. This level was then inserted as a serial digital data stream on the frequency-modulated transmission from Schomberg Peak and demodulated and recovered as the received level of that transmission was measured at Cockburn Peak. Both levels in turn were included in the FM serial digital data stream on the Cockburn Peak transmission, and the recovery and measurement process was repeated at the Lowther Peak receiver. The received levels of the transmissions from Cockburn Lake, Cockburn Flats, Allison Inlet, and Acland Acres were also measured at Lowther Peak. In addition, the levels of the transmissions from Cockburn Flats, Allison Inlet, and Acland Acres were measured at Lowther Beach and at Lowther Terrace and were telemetered to Lowther Peak. The Lowther Peak transmission to Martyr Peak thus had thirteen previous measurements encoded on it. At Martyr Peak the level of this last transmission was also measured, and all fourteen measured values were transmitted on a short range telemetry link to Resolute.

At all the UHF sites the antennas had four collinear half-wave folded dipole elements and a gain of 10.7 dBi, with two exceptions. The Lowther Peak UHF antenna receiving signals from Cape Cockburn was a cylindrical paraboloid with a gain of 17.2 dBi. After May 1984 only, the UHF antenna at Cockburn Peak had two, rather than four, collinear half-wave dipole elements and a gain of 7.7 dBi. All these antennas were vertically polarized and were mounted on six-metre towers so that the radiation centres of the collinear antennas were seven metres above ground and the cylindrical paraboloid was five metres above ground.

The VHF antennas at all sites had four collinear half-wave folded dipole elements with 10.7 dBi gain, except at both ends of the telemetry link from Martyr Peak to Resolute where single dipoles were used. All were vertically polarized and mounted on six-metre towers with their radiation centres nine metres above ground. On Lowther Island, the 72 MHz telemetry links from Lowther Beach and Lowther Terrace to Lowther Peak used single half-wave dipoles mounted on the sides of the main VHF antennas about eight metres above ground.

Path profiles of all the UHF links are shown in Figure 6, assuming an effective earth radius of 4R/3. The line of sight and the 0.6 Fresnel zone clearance are also shown. Path clearances at UHF range between almost one full Fresnel Zone on the link from Lowther Peak to Martyr Peak and zero on the link from Cockburn Lake to Lowther Peak. The path profiles at VHF are shown in Figure 7, assuming an effective earth radius of 4R/3. Here the path clearances range from near zero on the path from Acland Acres to Lowther Peak through increasingly negative values culminating at almost -1 Fresnel zone on the path from Cockburn Flats to Lowther Beach, as the paths are increasingly beyond the horizons. All paths at all frequencies were more than 90% over the sea, and, except possibly at Cockburn Flats, foreground blockage was negligible.

Because of the inaccessibility of the sites, all equipment was designed to operate unheated, unattended, and with minimal power consumption. Power was supplied by primary cells chosen for their good performance at extremely low temperatures. The transmitters used voltage-controlled oscillators which were phase-locked, after frequency division, to stable crystal oscillators in the 2 to 3 MHz range, and had nominal power outputs of 100 mW. The single-conversion receivers had simple mixer front-ends, and bandwidths of 12 kHz centred at 10.7 MHz IF. Quadrature detectors were used to demodulate the FM data stream of measured signal levels at each site.

All signal levels were recorded at the Ministry of Transport building at Resolute airport using a data cartridge recorder, with two cartridges being forwarded to Ottawa weekly for analysis. The sampling interval was 2.4 seconds, and the data were recorded as 8-bit binary numbers. Because of the non-linearity of the calibrations of the various receivers, the resolution of the measurements varied from about 0.15 dB to 1.5 dB over the 60 dB dynamic range of the equipment, and was typically about 0.3 dB.

The periods of operation on the various paths are summarized in Table 2. Above all, this table reveals the extreme difficulty of operating an experiment in one of the world's harshest environments. Outages at various times were caused by collapse of a tower structure, mechanical breakage of antennas, and destruction of RF cables and power cables by polar bears. In addition, some links could not be installed in September 1983, because the weather was too bad to allow helicopters to reach the sites. In the period April 22, 1984, to June 4, 1984, all the electronic equipment previously installed was removed for modification and recalibration. Although the Transfer Hill transmitter was installed in June 1984, and its signal was measured at Schomberg Peak immediately thereafter, when the recording system at Resolute was activated two days later no valid data were received from this link: this failure is yet to be diagnosed. The end of the present data set on January 7, 1985, resulted from the loss of the antenna at Martyr Peak on the link to Resolute MOT.

The almost complete absence of VHF data at Lowther Peak results from an antenna problem there which is not fully understood but is probably caused by a transmission line failure within the distribution network to the four dipoles. The symptom is random change of received signals between the levels predicted on the several paths and much lower unstable levels. This effect mimics to a certain extent the behavior expected during multipath fading and cannot be reliably separated from it, so that almost all VHF data at Lowther Peak have been discarded. The exceptional two-week period in July 1984 has been included for comparison with the behaviour of other links, but clearly is too short and unrepresentative to be of much value for predictive purposes. Finally, the VHF data from Cockburn Flats and Acland Acres to Lowther Peak, gathered in the fall of 1982 and reported by Butler, et al. (1984), are now perceived to have been hopelessly corrupted by this same problem, and the guarded conclusions drawn in that report concerning those data have to be withdrawn.

4. DATA REDUCTION AND ANALYSIS

The AGC levels from each link were averaged over one minute, calibrated, and plotted as a function of time in half-day periods for visual inspection. This inspection allowed occasional short outages and recording errors to be detected and then cleaned from the final results. After the cleaning process the data were sorted into bins at each digital level and statistical distributions were thus produced for each month when any link was working. Medians were calculated and the distributions for each month (or part month) were plotted on both log-log and log-normal scales. The "seasonal" and some overall distributions were similarly produced and plotted.

Table 2 Periods of Operation of Experimental Links

Name	Start	Stop
Transfer Hill - Schomberg Peak	--	--
Schomberg Peak - Cockburn Peak	June 4, 1984	Jan. 7, 1985
Cockburn Peak -Lowther Peak	Sept. 2, 1983 June 4, 1984	Nov. 10, 1983 Jan. 7, 1985
Cockburn Lake - Lowther Peak	Sept. 2, 1983 Aug. 3, 1984	Oct. 20, 1983 Jan. 7, 1985
Lowther Peak - Martyr Peak	Sept. 2, 1983 June 4, 1984	April 22, 1984 Jan. 7, 1985
Cockburn Flats - Lowther Beach	Sept. 2, 1983 June 4, 1984	Nov. 21, 1983 Oct. 11, 1984
Cockburn Flats - Lowther Terrace	Sept. 2, 1983 June 4, 1984	Nov. 21, 1983 Jan. 7, 1985
Cockburn Flats - Lowther Peak	(July 10, 1984)	(July 25, 1984)
Allison Inlet - Lowther Beach	Sept. 2, 1983 June 4, 1984	Nov. 21, 1983 Oct. 8, 1984
Allison Inlet - Lowther Terrace	Sept. 2, 1983 June 4, 1984	Nov. 21, 1983 Jan. 7. 1985
Allison Inlet - Lowther Peak	(July 10, 1984)	(July 25, 1984)
Acland Acres - Lowther Beach	Sept. 2, 1983	Nov. 21, 1983
Acland Acres - Lowther Terrace	Sept. 2, 1983 Aug. 3, 1984	Nov. 21, 1983 Sept. 12, 1984
Acland Acres - Lowther Peak	--	--

Because the seasons of temperate climatic zones have no meaning in the Arctic, the choice of significant periods into which the data could be divided required some analysis, which was complicated by the disjoint operating times of the links. The final choice was to use three "seasons": "summer", the months May to August, which corresponds to the period of continuous daylight; "fall-winter", the months September to December, when freeze-up occurs and the Arctic night sets in; and "winter-spring", January to April, a time of continuous snow and ice cover when the Arctic temperature inversion is most widespread. Other choices might have been made had the data been more evenly distributed throughout the year. However, since only one link ever operated in the January to April period, and there are no May data at all, this choice seems most plausible. As will become apparent below, the observed activity on the links falls naturally into these three "seasons". A "season" is about 10^7 seconds.

4.1 UHF Data

4.1.1 Annual and Seasonal Statistics

The longest and most complete set of data was obtained on the path from Lowther Peak to Martyr Peak. The daily median values of received signal level for this link are shown in Figure 8. The internal consistency of the data is excellent, with the 1983/84 and 1984/85 winter measurements agreeing to better than 1 dB on a monthly median basis. The days of reduced median signal level correspond to fading activity on the link and it appears that, during the winter, active periods lasting for three or four days can occur. Generally, however, the winter seasons have high and stable signals, in contrast to the summer when fading activity occurs on most days. The transition from summer to fall-winter at the start of September 1984 is especially striking, although this may be a statistical oddity since in September 1983 fading activity did not end so abruptly. The increase in activity in April 1984 as summer approaches should also be noted. Results compatible with these were found on all the UHF links, although with less extensive sets of data.

Figure 9 shows the cumulative annual probability distribution of received signal level on the path Lowther Peak to Martyr Peak for 1984. Received levels below the median can be approximated by a log-normal curve with a maximum discrepancy of about 2 dB, while the levels above the median clearly do not share this behaviour. Such asymmetry is characteristic of long-term fading in maritime temperate climates (Rice et al., 1967; Whitteker, 1985), based on the distribution of hourly medians, but the asymmetry of the distribution is much greater here. Although the distribution of Figure 9 has a time resolution of a few seconds, a similar distribution based on hourly median values shows exactly the same behaviour between the 1% and 99% fractions of time, where the statistical validity is highest. The greater asymmetry observed here, especially the relative absence of signal levels much greater than the median, may thus be characteristic of the Arctic maritime environment.

The "seasonal" distributions of the received signal levels on the path Lowther Peak to Martyr Peak are shown in Figure 10. It is striking that all the measurements of signal level greater than the median during the months September to April, both in 1983 and 1984, are consistent with each other, while in summer 1984 the median and the levels exceeding it are generally lower. The difference between the faded signal levels in fall-winter of 1983 and of 1984 is also very striking as it exceeds 30 dB for small fractions of the time. Finally, it appears that very deep fades, exceeding 30 dB below the annual median, can occur for similar fractions of time in all seasons.

For the other UHF paths, the span of the observations is too short to allow annual statistics to be accumulated. However, the seasonal distributions of received signal level are presented in Figures 11, 12, and 13, for fall-winter 1983, summer 1984, and fall-winter 1984, respectively. These figures all include data on the Lowther Peak - Martyr Peak path for comparison purposes. The precise length of the record for each curve in these figures may be deduced from Table 2, and is quite variable. As a result, comparisons among these distributions must be made with a great deal of caution.

The differences on the various UHF paths between the distributions in the fall-winter seasons of 1983 and 1984 are remarkably great, exceeding 20 dB for moderate fractions of time on most of the paths. On all paths, however, fading is most severe in the summer season. It appears that this effect extends to all signal levels, including those above the median, which in summer are also lower than during fall-winter.

In Table 3 are collected the observed median signal levels on all the paths for various time spans, with respect to the long term medians calculated from the CRC propagation prediction program and the known link parameters. The "effective distance" in this table is calculated from the formula given by Rice, et al (1967) and is said to give better empirical correlation with long-term fading than the geographical distance. The "excess length of the reflected path" in the table is calculated as the difference of length of the direct ray and the ray reflected from the sea for an effective earth radius of 4R/3. On the three paths which have only a small Fresnel zone clearance, the predicted path loss exceeds the free space loss by the amounts given in the table, again assuming 4R/3 effective earth radius.

There is a tendency in Table 3 for the seasonal medians to exceed the predicted medians by several dB, except in summer. For the three longest paths, which have considerable Fresnel zone blockage, the trend of the median excess is the same as the trend of the predicted excess loss over free space. It is likely that this occurs partly because the effective earth radius is less than the value 4R/3 used in the prediction, as this is compatible with the data of Figure 4. The exception to the trend is the link from Lowther Peak to Martyr Peak, which has no excess path loss for an effective earth radius of 4R/3. Since flattening the earth will not enhance the received signal on this link, at least some of the increase of the medians here results from ducting. Consequently, it is expected that ducting must contribute to the enhanced medians on the other links as well, since the path geometries are qualitatively similar. In summer on all links the discrepancies between observed and predicted median levels also follow the trend of the predicted excess loss over free space, but there are negative as well as positive values. In fact the path with the greatest blockage shows relatively the highest median, while the clearest path has the lowest. This may result because, on the link furthest beyond the horizon, multiple ray trajectories can occur only in very unusual atmospheric conditions, while multipath propagation, including reflections, can occur more readily on the clear link.

Table 3

a) Parameters of the UHF Paths

	Schomberg Peak Cockburn Peak	Cockburn Peak Lowther Peak	Cockburn Lake Lowther Peak	Lowther Peak Martyr Peak
Distance (km)	91.0	98.8	96.5	72.9
Effective Distance (km)	80.7	84.9	91.8	61.7
Excess length of reflected path (wavelengths)	0.05	0.03	-	0.49
Predicted loss excess over free space (dB)	4.0	9.4	16.9	0.0
Predicted median (dBm)	-96.7	-94.5('84) -91.5('83)	-96.9	-83.6

b) Observed Median Levels - Predicted Medians (dB)

	Schomberg Peak Cockburn Peak	Cockburn Peak Lowther Peak	Cockburn Lake Lowther Peak	Lowther Peak Martyr Peak
Annual, 1984	-	-	-	5.0
Fall-Winter 1984	5.5	8.8	9.7	5.7
Summer 1984	0.6	1.4	-	-4.0
Winter-Spring 1984	-	-	-	6.4
Fall-Winter 1983	-	1.6	2.8	4.3

Some further evidence that ducting occurs on these paths may be seen from Figures 11, 12, and 13 where levels greatly exceeding the median exist for appreciable fractions of time. As an example, in Figure 11 in

Table 4 Signal Levels Relative to the Predicted Medians for Selected Fractions of Time on UHF Paths (dB)

	Fall-Winter 1983			Winter-Spring 1984			Summer 1984			Fall-Winter 1984		
	1%	0.1%	0.01%	1%	0.1%	0.01%	1%	0.1%	0.01%	1%	0.1%	0.01%
Schomberg Peak - Cockburn Peak	-	-	-	-	-	-	-32.6	<-37	-	-2.1	-3.2	-12.5
Cockburn Peak - Lowther Beach	-16.8	-20.1	-27.3	-	-	-	-25.2	-31.8	<-38	+2.2	-3.7	-15.7
Cockburn Lake - Lowther Peak	-16.4	-22.0	-25.5	-	-	-	-	-	-	+7.0	+2.3	-7.1
Lowther Peak - Martyr Peak	-6.9	-13.8	-24.9	-10.9	-21.5	26.6	-16.5	-21.6	-25.2	+1.5	-0.3	-0.8

fall-winter 1983 on the path Cockburn Lake to Lowther Peak for 0.01% of the time the level exceeds the seasonal median by 23 dB (99.99% probability level not exceeded). Since this seasonal median is itself 2.8 dB above the predicted value and the excess loss over free space is 16.9 dB, the observed value for 0.01% of time exceeds free space propagation levels by about 9 dB. Similar excesses occur on all the paths, and in all seasons.

Some statistics of the depths of fade observed for certain percentages of the time are collected in Table 4. Perhaps the most striking observation in this table is the great difference between the fall-winter data in 1983 and 1984, as compared with the differences between seasons. In all seasons the path from Lowther Peak to Martyr Peak exhibits the least deep fading, although deep fading does occur. It appears that the summer season is when the deepest fades are observed and that very deep fades, exceeding 40 dB, may occur for small fractions of the time, at least on some paths. No summer 1984 seasonal statistics are available for the path Cockburn Lake to Lowther Peak, which was operational only for the month of August in that season, but on the basis of the data which are available fading on this grazing path will be no more severe than on the paths with relatively little Fresnel zone blockage.

4.1.2 Worst-Month Statistics

The month exhibiting the worst fading not only depends on the fade depth, but also is very dependent on the span of the observations. It is clear that fading events are most common in summer, yet the deepest fades on the path Lowther Peak - Martyr Peak observed in the present experiment occurred in October 1983, and by contrast October 1984 was remarkable for an absence of fading. In Figure 14 the monthly distributions for October 1983 and August 1984 are presented. Moderate fading of about 20 dB below the annual median occurs for 1% of August but for only 0.1% of October, while deep fading of 40 dB occurred for 0.005% of October but not at all in August.

The worst-month statistics on the UHF paths Schomberg Peak - Cockburn Peak, Cockburn Peak - Lowther Peak and Cockburn Lake - Lowther Peak, are presented in Figure 15. The worst month at all signal levels was July 1984, for both Schomberg Peak - Cockburn Peak and Cockburn Peak - Lowther Peak. For the Cockburn Lake - Lowther Peak link the worst month was September 1983 at all levels. This link was not operational in July of 1984, so it is possible that a worse month existed but was not recorded. However, in all the months when all three links were operating the order of severity of fading was the same as in Figure 15, i.e., fading was generally most severe on the link from Schomberg Peak, intermediate on the link from Cockburn Peak, and least severe on the link from Cockburn Lake. This is exactly the order of decreasing clearance on the various paths, and it may be that on near-grazing paths atmospheric conditions extreme enough to cause deep fading are much rarer than on paths with less Fresnel zone blockage. However, the path Lowther Peak - Martyr Peak, which has the greatest clearance, does not follow the trend, as comparison with Figure 14 shows that almost over the whole range of levels this path has the smallest probability of fading. An alternative explanation for the order of severity of fading is purely geographic. As discussed in section 2, there is a considerable difference in fractional ice cover along the east-west extent of the Parry Channel, and related differences in the structure of the lower atmospheric layers are to be expected. Since the links from Cockburn Peak and Cockburn Lake to Lowther Peak are nearly coincident, differing mainly in path clearance, a combination of the two explanations is probably necessary, but their relative importance cannot be judged at present.

In Table 5 some statistics of the worst-month fading on the UHF paths are collected for ready comparison, with the numbers calculated as (observed level at given probability - predicted long term median). One month is approximately 2.6 x 10^6 seconds.

Table 5 Worst-month UHF Signal Levels Relative to Predicted Long-term Median (dB)

Fraction of month	Schomberg Peak Cockburn Peak	Cockburn Peak Lowther Peak	Cockburn Lake Lowther Peak	Lowther Peak Martyr Peak
50%	-5.1	-5.0	+2.5	-6.6
1%	-32.9	-27.3	-18.0	-18.0
0.1%	<-34	-32.1	-23.3	-22.8
0.01%	-	<-36	-25.6	-34.5

4.1.3 Diurnal Variations

The data on the Lowther Peak - Martyr Peak path in each calendar month of 1984 were grouped into 24 bins corresponding to the hours of the day, so that any diurnal variation in a month could be detected. The results are shown in Figure 16, where each plotted point is the median value at its hour of the day of all the measurements in that hour for that month. The annual median is shown as a straight line in all the plots. The lack of diurnal variation in the months January to March and September to December is very striking. In each of these months the observed values are consistently above the annual median, with a maximum difference of about 2 dB occurring in February. In April, a reduction of signal by about 3 dB from the monthly median occurs between midnight and 0800 local time. As discussed in section 2, the duration of daylight increases from about 14 to 24 hours, so that there is a daily cycle of daylight and dark, during April.

In June, July, and August, the diurnal variation of median signal levels is extremely pronounced, with a diurnal amplitude of 4 to 6 dB, the maximum occurring near 0400 hours in each month. The level is a minimum, and in each month nearly constant, from about 1000 to 1900 hours, and is typically 10 to 12 dB below the annual median. Through the whole of this period, except for the last two weeks of August, the sun is continuously above the horizon.

The present observations of diurnal variation are rather similar to those in temperate maritime regions (Whitteker, 1985) but differ in having both maximum and minimum levels which are farther below the median in summer, and in having a consistent unvarying enhancement of signal level in winter. The variation observed in April as winter ends appears to be unique to the present observations.

4.2 VHF Data

4.2.1 Seasonal Statistics

The periods of measurement on the various VHF paths, as listed in Table 2, are too short for annual statistics to be derived, and for some of the paths even seasonal statistics are not available. Thus intercomparisons of the data from these paths must be made with caution. Some parameters of the VHF paths are listed in Table 6. The "distance beyond horizon" is the difference (geographic distance - sum of distances to geometric horizons, for earth radius 4R/3) and is negative if the ends of a path are within line of sight. "Effective distance" and "excess loss" have the same meaning as in Table 3 for the UHF paths. All the paths but

Table 6 VHF Path Parameters

	Geographical Distance (km)	Distance Beyond Horizon (km)	Effective Distance (km)	Excess Loss (dB)	Predicted Median (dBm)
Cockburn Flats - Lowther Beach	88.4	48.6	121.2	42.1	-123.4
Allison Inlet - Lowther Beach	74.3	32.3	99.5	38.6	-111.6
Acland Acres - Lowther Beach	60.1	18.5	80.9	33.8	-105.0
Cockburn Flats - Lowther Terrace	90.6	27.3	99.5	32.8	-114.3
Allison Inlet - Lowther Terrace	76.4	10.9	82.4	27.9	-101.1
Acland Acres - Lowther Terrace	62.2	-2.9	67.3	21.9	-93.4
Cockburn Flats - Lowther Peak	93.8	16.0	91.8	27.9	-109.7
Allison Inlet - Lowther Peak	79.6	-0.4	76.6	23.8	-98.7
Acland Acres - Lowther Peak	65.2	-14.4	62.9	16.1	-88.0

one are near or beyond the sum of their horizon distances. In the extreme case, Cockburn Flats to Lowther Beach, the difference is comparable to the distance, 55.1 km, at which the diffracted and scattered fields are equal (Rice, et al. 1967). On all paths the excess loss is quite large.

The cumulative distributions of received signal level on the paths to Lowther Beach are presented in Figures 17, 18, and 19, for fall-winter 1983, summer 1984, and fall-winter 1984 respectively. Because of limited dynamic range there is little fading information on the link from Cockburn Flats, while from Allison Inlet the fading range provides data to slightly beyond 1% probability, although for only one season in this last case. There is substantial correlation among the results for all three seasons of observation, with the summer data not differing substantially from the fall-winter data, in strong contrast to the results on the UHF paths.

In Figures 20, 21, and 22, the cumulative distributions of received signal level on the paths to Lowther Terrace are presented for fall-winter 1983, summer 1984, and fall-winter 1984, respectively. Here the dynamic ranges are considerably greater than on the paths to Lowther Beach but as in the case of the Lowther Beach data, there is no strong seasonal dependence apparent. Also, as might be expected from the parameters given in Table 6, there is a high correlation between the path pairs Cockburn Flats - Lowther Terrace and Allison Inlet - Lowther Beach. This emphasizes that distance beyond the horizon, or perhaps effective distance, is a critical parameter in the fading behaviour on a path, while the elevation of the ends of the path is of secondary importance except as it affects this distance. It is also noteworthy that on the path from Acland Acres to Lowther Terrace the form of the distributions is different from all the others, and rather resembles the behavior noted on the UHF paths. This may well be a real difference which arises because this is a line of sight path, comparable to the UHF link Cockburn Lake - Lowther Peak, while the others go well beyond line of sight. However, the data sample is too small for this to be other than a speculative suggestion.

There is no extensive set of data on the paths to Lowther Peak, as discussed in Section 3. However, in Figure 23 the distributions for a two week period in July 1984 are presented for the paths from Cockburn Flats and Allison Inlet to Lowther Peak, and also to Lowther Terrace for comparison purposes. This is by no means a representative data sample; it is merely the longest continuous data sequence that was thought to be reliable. Within this very short time period, it is clear that there is no substantial qualitative difference between the distribution of signals received at Lowther Terrace and those at Lowther Peak, and the quantitative differences are in the order expected from Table 6.

The median signal levels observed on the VHF paths are listed in Table 7 for each seasonal distribution, relative to the predicted long-term medians. The agreement is quite good at all seasons, with perhaps a tendency for the observed values to average about 3 dB lower than predicted. However, the data set is not adequate for this to be concluded firmly. The internal agreement among various pairs of paths is also quite good, and allows the confident expectation that the prediction program will provide satisfactory numbers for a system design. For the data of mid-July on the paths to Lowther Peak, the median signal on the path from Cockburn

Flats is -3.0 dB from that predicted, while the median signal on the path from Allison Inlet is exactly the same as predicted. On the paths to Lowther Terrace at this time the observed relative medians are -0.1 dB and -2.2 dB from those predicted for Cockburn Flats and Allison Inlet, respectively. Again the agreement is remarkably good.

Table 7 Observed VHF Medians Relative to Predicted Values (dB)

	Fall-Winter 1983	Summer 1984	Fall-Winter 1984
Cockburn Flats - Lowther Beach	-2.7	-0.5	-3.6
Allison Inlet - Lowther Beach	-5.3	-3.3	-5.1
Acland Acres - Lowther Beach	-3.4	-	-
Cockburn Flats - Lowther Terrace	-2.8	1.4	2.8
Allison Inlet - Lowther Terrace	-5.2	-1.7	-1.7
Acland Acres - Lowther Terrace	-1.0	-0.7	-0.6

Signals much greater than the median are observed for significant fractions of time on all paths. As an example, in Figure 17 in the fall-winter season of 1983 on the paths to Lowther Beach, the observed levels exceeded for 0.01% of the time (not exceeded for 99.99% of the time) are 24.2, 19.3, and 16.5 dB respectively above the long-term predicted medians from Cockburn Flats, Allison Inlet, and Acland Acres. Even these large enhancements are only about half the excess loss from diffraction on these paths, as seen from Table 6. Similar results are found for all the paths in all the seasons, excluding the paths to Lowther Peak for which no conclusions can be drawn.

The observed fade depths for certain percentages of time, relative to the predicted median, are presented in Table 8. Because of limited dynamic range, many of the entries in this table are uninformative. It is possible to extrapolate the seasonal graphs presented earlier to get an estimate of fade depths at smaller percentages of time, but that has not been done here. It appears that the differences between the same season in different years can be larger than the season-to-season difference in a given year. The relative lack of fading in fall-winter 1984 parallels that observed on the UHF links. For the best sets of observations the fade depths observed are smaller than those on the UHF links, and there also may be less variation among the VHF paths than among the UHF paths, but the data are not adequate to establish this conclusion firmly. The parentheses on the summer 1984 data from Acland Acres to Lowther Terrace call attention to the short span of this data set.

Table 8 Signal Levels Relative to the Predicted Medians for Selected Fractions of Time on VHF Paths (dB)

	Fall-Winter 1983			Summer 1984			Fall-Winter 1984		
	1%	0.1%	0.01%	1%	0.1%	0.01%	1%	0.1%	0.01%
Cockburn Flats - Lowther Beach	<-9	-	-	<-7	-	-	<-7	-	-
Allison Inlet - Lowther Beach	-17.6	<-21	-	-15.9	<-19	-	-17.7	<-19	-
Acland Acres - Lowther Beach	-17.8	-27.0	<-28	-	-	-	-	-	-
Cockburn Flats - Lowther Terrace	-15.3	<-18	-	-11.9	<-18	-	-8.1	-9.1	-11.0
Allison Inlet - Lowther Terrace	-13.5	-24.5	-31.1	-13.6	-23.7	<-29	-7.0	-14.2	-25.4
Acland Acres - Lowther Terrace	-17.5	-18.9	-19.8	(-4.6)	(-7.4)	(-14.6)	-	-	-

4.2.2 Worst-Month Statistics

The cumulative distributions of signal levels observed on each VHF path during the worst month of the experimental period are presented in Figure 24. Once again, because the length of record is quite different on the various paths, these results must be viewed with a certain amount of caution. Nevertheless, there is a great deal of similarity in the worst month signal distributions on five of the six paths, all of which extend to or beyond the common horizons of the path end points. Only the path Acland Acres to Lowther Terrace is line-of-sight, and the distribution on this path is rather different from the others, as it also was for the seasonal distributions presented earlier.

The worst month was September, 1983, on the paths Cockburn Flats to Lowther Terrace, Allison Inlet to Lowther Beach, Acland Acres to Lowther Beach, and Acland Acres to Lowther Terrace, although in the last case there are no 1984 data for comparison. On the path Cockburn Flats to Lowther Beach the worst month was October, 1983, while on the path Allison Inlet to Lowther Terrace it was July, 1984. Overall, the months which are worst months appear to be the same on both VHF and UHF paths.

Some statistics of worst-month fading on the VHF paths are collected in Table 9, where the numbers are (observed level at a given probability minus predicted long-term median). Unlike the situation on the UHF paths, summarized in Table 5, there are great similarities amongst these statistics for the various VHF paths. Thus, all the worst-month medians are 3 to 5 dB lower than the predicted medians, and for 1% of the month all the levels are 16 to 20 dB lower. This greater consistency probably occurs in part because all the paths are in the same small geographic area, and all are well within the zone where propagation is strongly dominated by diffraction.

Table 9 Worst-month VHF Signal Levels Relative to Predicted Long-term Medians

	Fraction of Month			
	50%	1%	0.1%	0.01%
Cockburn Flats - Lowther Beach	-5.6	<-7	-	-
Cockburn Flats - Lowther Terrace	-3.2	-16.7	<-17	-
Allison Inlet - Lowther Beach	-4.9	-18.4	<-19	-
Allison Inlet - Lowther Terrace	-2.5	-19.6	-27.2	<-29
Acland Acres - Lowther Beach	-3.7	-20.1	<-26	-
Acland Acres - Lowther Terrace	-2.0	-18.4	-19.4	-20.0

5. CONCLUSION

5.1 Summary of Results

The central region of the Canadian Arctic islands is an area of great variability of radio propagation conditions, both seasonally and from year to year. In general, propagation is most stable during the period of winter darkness (although strong exceptions to this rule may occur), and is most variable during the period of continuous daylight, when there is a significant diurnal variation of signal medians on the elevated UHF paths. The form of the cumulative distribution of signal levels on the single elevated path for which annual statistics are available is very asymmetrical about the median, and log-normal for levels below the median. The trend of differences from predicted annual values for both seasonal and worst-month medians on the elevated paths seem to correlate with path clearance and with geographical location, but the two effects cannot be adequately resolved from the present measurements. Ducting occurs on all the elevated paths, with signals greater than the free space level observed in all seasons, but especially in winter.

On the slant VHF paths to and beyond the horizon, there is good agreement of observation with theoretical predictions of median signal levels. Year-to-year and season-to-season variability on these paths is much less than on the elevated UHF paths, and no diurnal variation is apparent. While levels well above the median are observed on all the slant paths, these never attain the free-space signal level.

5.2 Interim Recommendations

An unpublished report (Dubinski, 1982) of a preliminary study by the present author of the possibility of a maritime mobile telecommunication system in the Northwest Passage concluded that the region most inaccessible to shore-based VHF transmissions is near latitude 74° 20'N, longitude 103° 20'W, in Viscount Melville Sound. There the predicted median path loss at 170 MHz would be about 150 dB. Except for a small irregular region near this point the greatest predicted median path losses elsewhere rarely exceed 140 dB, for plausible choices of shore transmitter locations.

From the measurements presented in section 4.2.1 it appears that an additional margin of 20 dB will allow communications for all but 1% of the worst month. Thus a system designed for a path loss of 170 dB would have such reliability even to the most inaccessible part of Viscount Melville Sound, and reliability of 0.1% of the worst month (or better) almost everywhere else. As an indicator of magnitude, with a receiver having a threshold of -120 dBm and using 16 dBi net total antenna gain on the ship/shore path, this performance would require a single channel transmitter power of +34 dBm, or 2.5 watts.

The same unpublished study concluded that the greatest median path loss on a land-based chain from Baffin Bay to Amundsen Gulf, circling the northern side of the Passage, would be 135 dB on the link Cockburn Peak to Lowther Peak. The present results indicate that on this 99 km path a margin of 32 dB beyond the predicted median path loss will allow communication for all but 0.1% of the worst month. With a -120 dBm receiver threshold and a net total gain of +34 dBi, this performance would require a single channel transmitter power of only +13 dBm, or 20 mW. If it were desired to cover the Passage completely by including a set of transmitters on the southern side, one link in that chain has been identified which has a predicted median path loss of 146 dB. The 96 km link from Cockburn Lake to Lowther Peak, with a predicted path loss of 142 dB, was chosen to simulate this 99 km southern link. Using the observed margin of about 24 dB for 0.1% of the worst month together with the other parameters above, the required single channel transmitter power is +16 dBm, or 40 mW. On all the other links of the chain such a design would produce comparable or higher reliability, better than 0.01% of the worst month in many cases.

In designing a system frequency plan the highest received levels of the present study can be used to develop interference criteria. It appears that on elevated paths with positive Fresnel zone clearance a level exceeding the predicted free-space path loss by 9 dB may be experienced for 0.01% of a season. On slant paths extending to or beyond the horizon, or for long over-the-horizon paths between a pair of points at low elevation, the maximum observed levels for 0.01% of a season exceed the predicted long-term medians by about one-half the predicted loss excess over free space, in decibels.

A system designed to the specifications above seems reasonably assured of success. However, for greater confidence it is desirable to extend the measurement program in time, to guard against anomalies in annual statistical behaviour, and in space, to check that significant climatic variations do not occur.

6. ACKNOWLEDGEMENTS

The conceptual design of much of the experiment, and especially of the data recording system, was the work of John Strickland, whose seemingly tireless efforts both in the field and the laboratory were indispensible to whatever measure of success has been achieved. Claude Bilodeau was responsible for the design and execution of all the RF equipment, and produced remarkable results in the face of minimal resources and tight time schedules.

I am grateful to Ray Bérubé, Roger Charron, Rachel Lessard, Doris Oxton, and above all to Keith Bedal, for their numerous contributions to the project, especially in the field.

The Telecommunications and Electronics Branch of the Canadian Coast Guard has maintained a close interest in the Northwest Passage Experiment, funding an extension of the presently reported measurements, and arranging for support at Resolute of the data recording system. I would like to thank A.K. Khan, Superintendent of Communications systems, and Dick Galvin, Telecommunications Area Manager at Resolute, for their invaluable co-operation.

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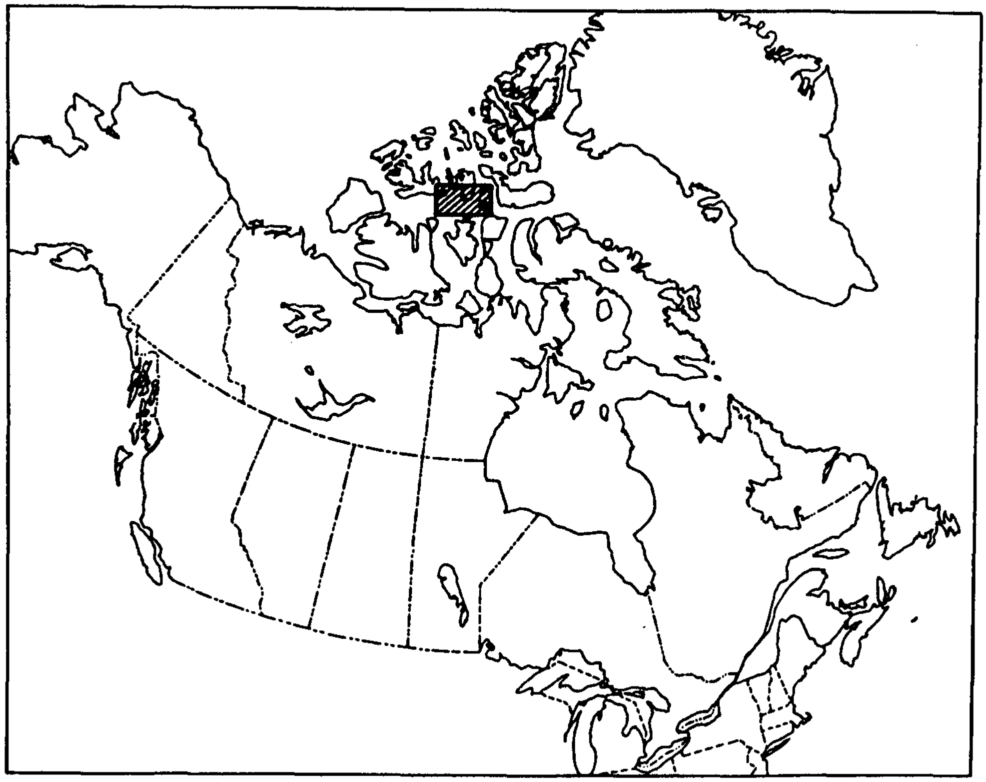


Figure 1: Canada, with the experimental region indicated in the central Arctic islands.

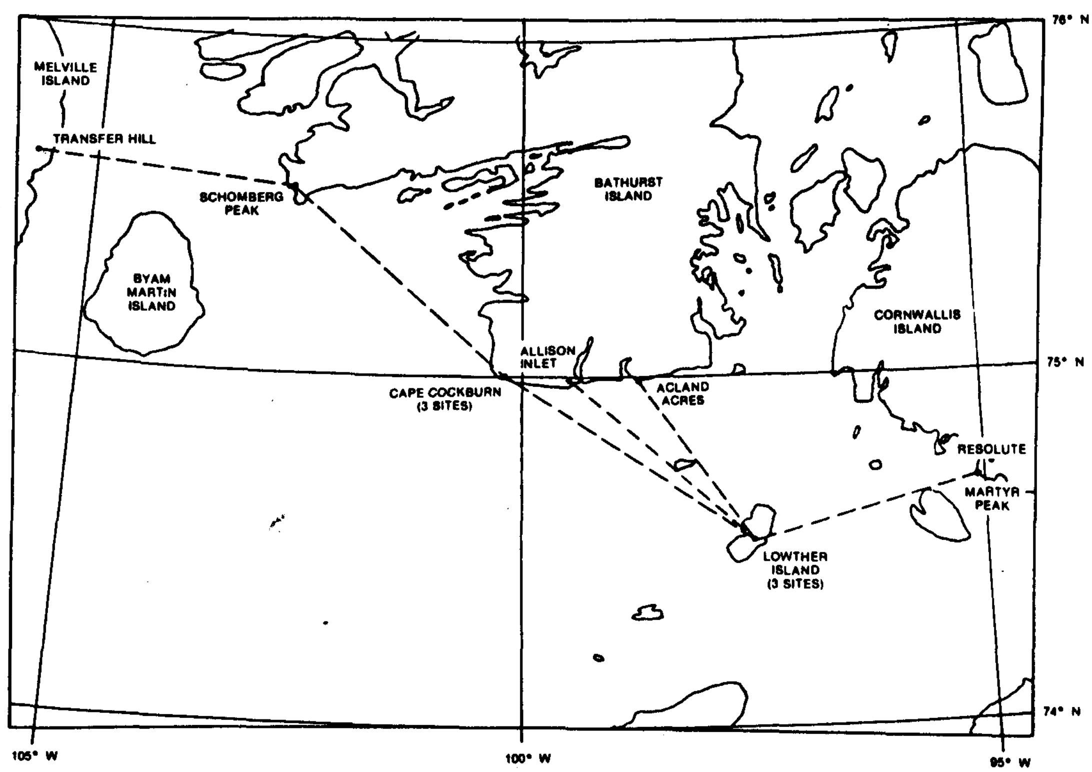


Figure 2: The experimental region, showing equipment locations and propagation paths.

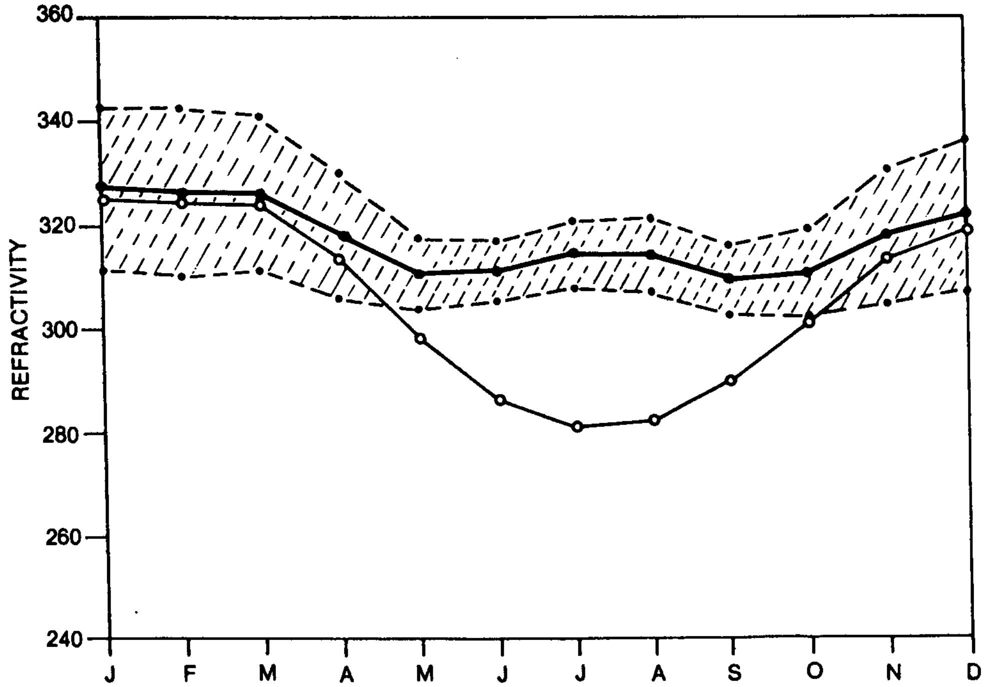


Figure 3: Monthly means (solid circles) and 95% probability limits (shaded band) for surface refractivity, and monthly means (open circles) of its dry air component, at Resolute, NWT.

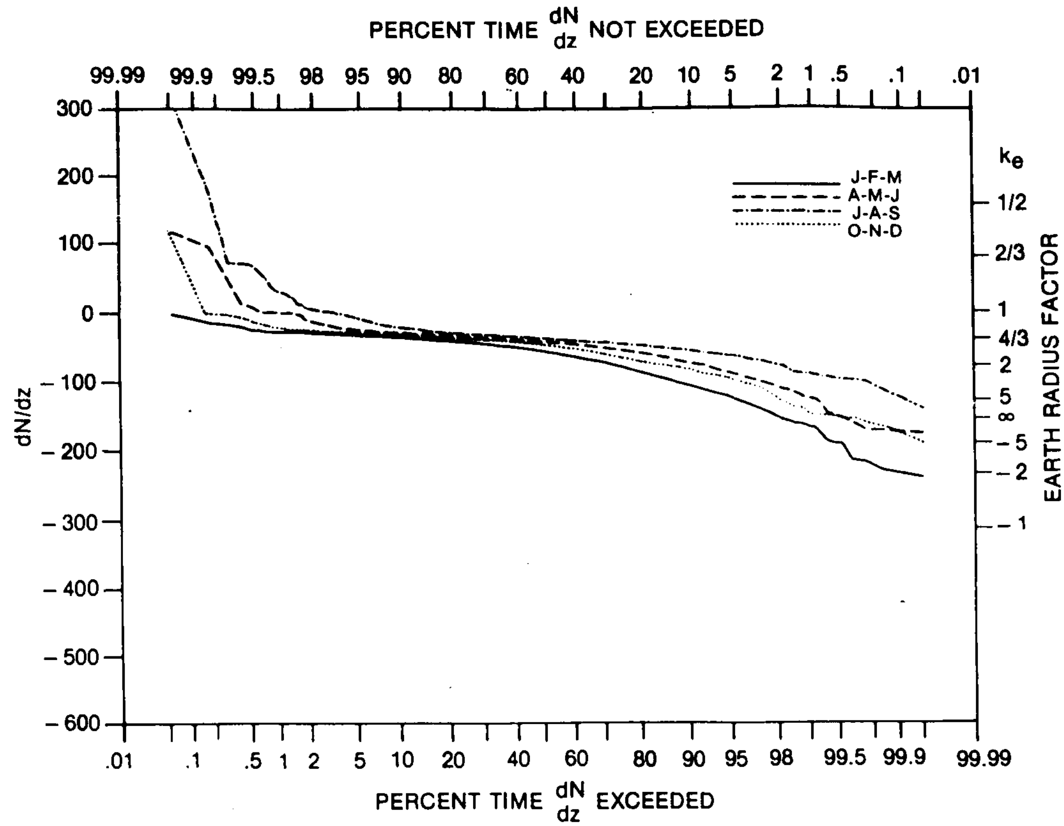


Figure 4: Seasonal probability distributions of ground-based refractivity gradient at Resolute, NWT.

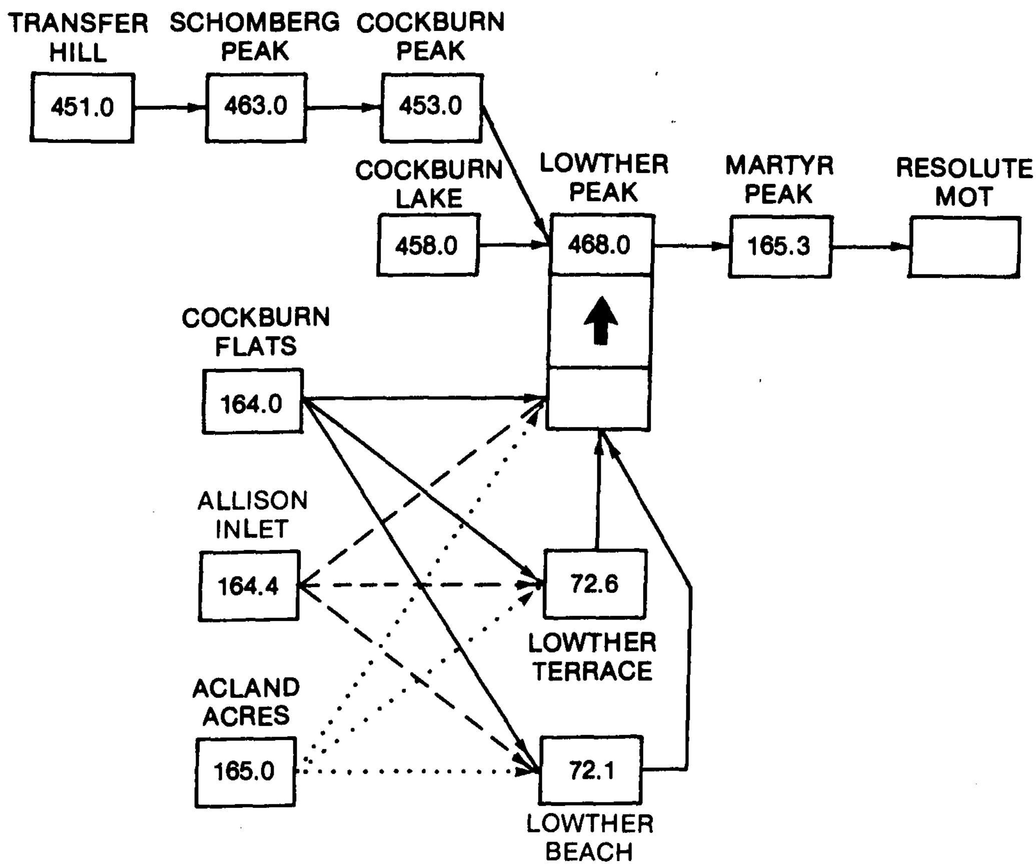


Figure 5: Experimental links, with transmitter frequency given (in MHz) for each site.

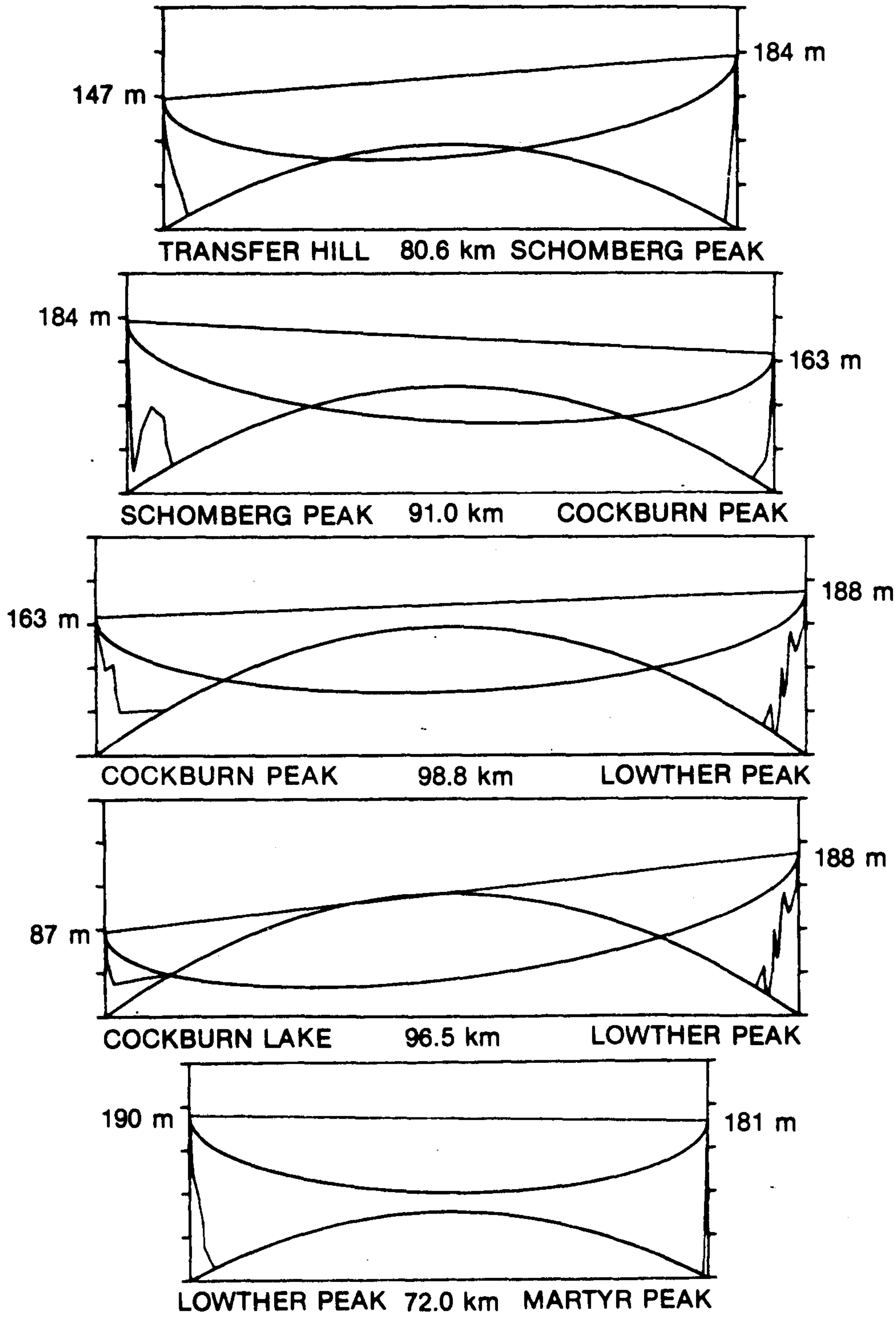


Figure 6: Profiles of the UHF paths, with effective earth radius 4R/3 and the 0.6 Fresnel zone clearance shown.

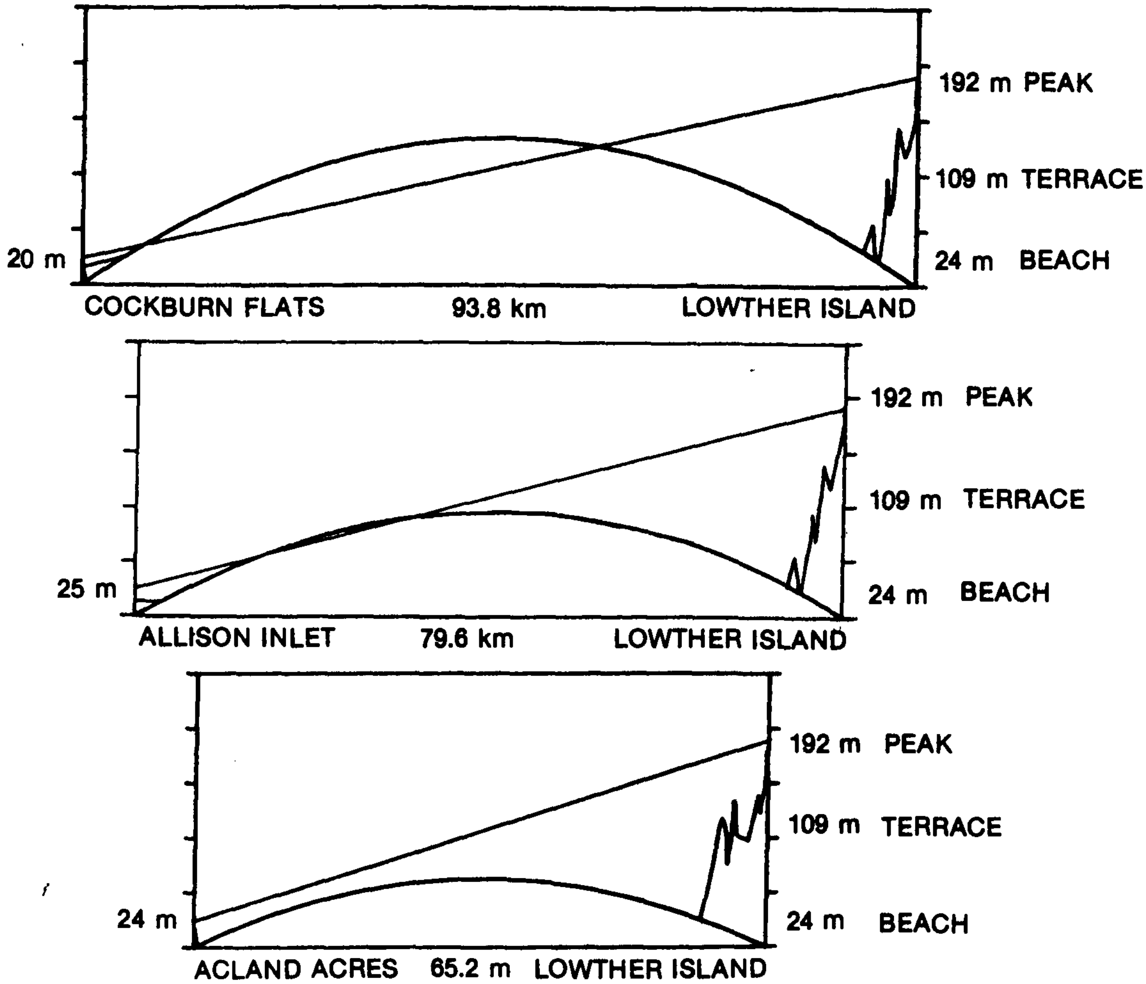


Figure 7: Profiles of the VHF paths with effective earth radius 4R/3. The lines to Lowther Terrace and Lowther Beach have been omitted for clarity.

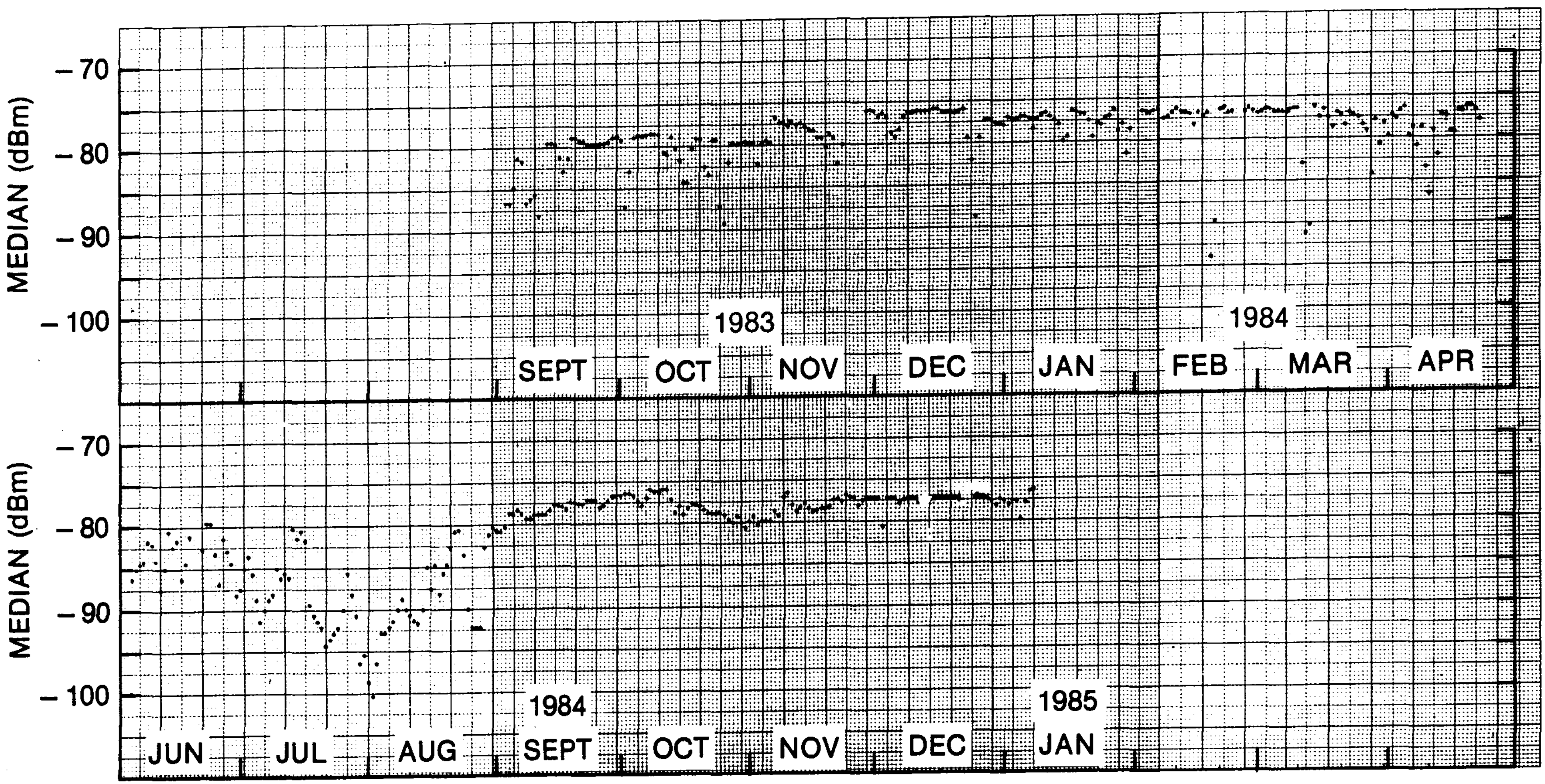
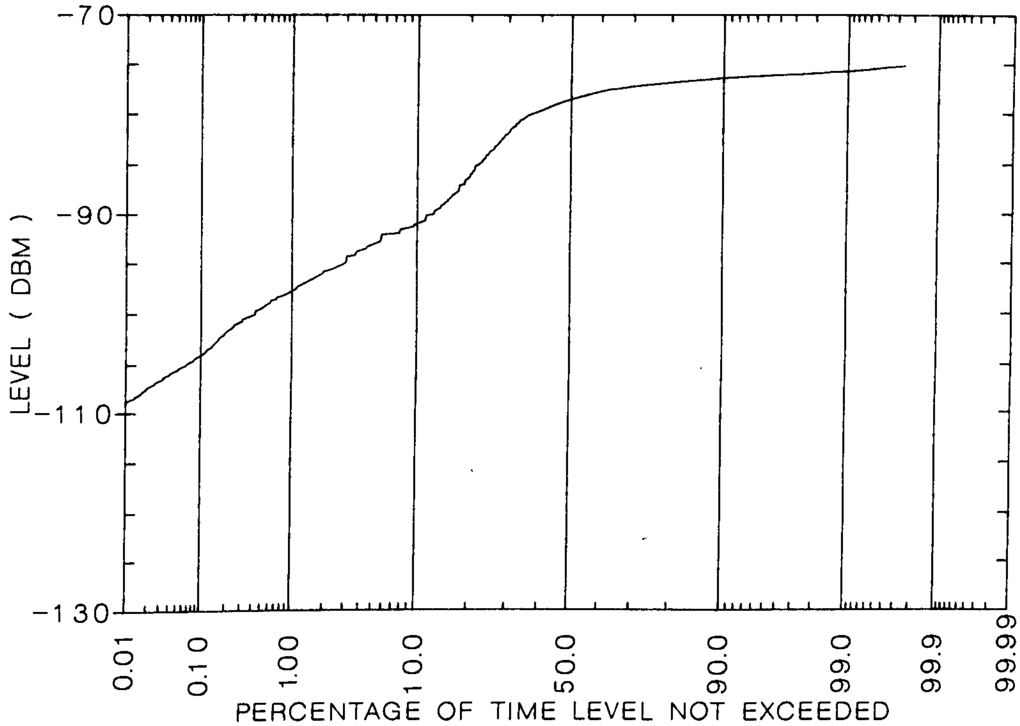


Figure 8: Daily median signal levels, Lowther Peak - Martyr Peak.



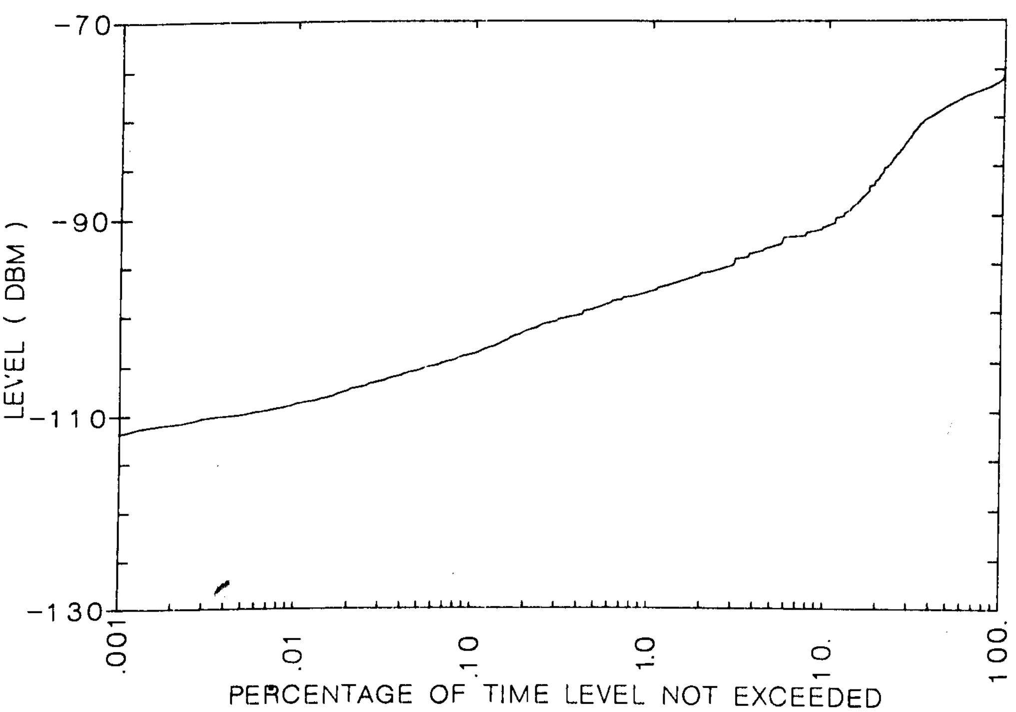


Figure 9: Annual statistics, Lowther Peak to Martyr Peak, 1984.
Upper: Log-normal; Lower: Log-log.

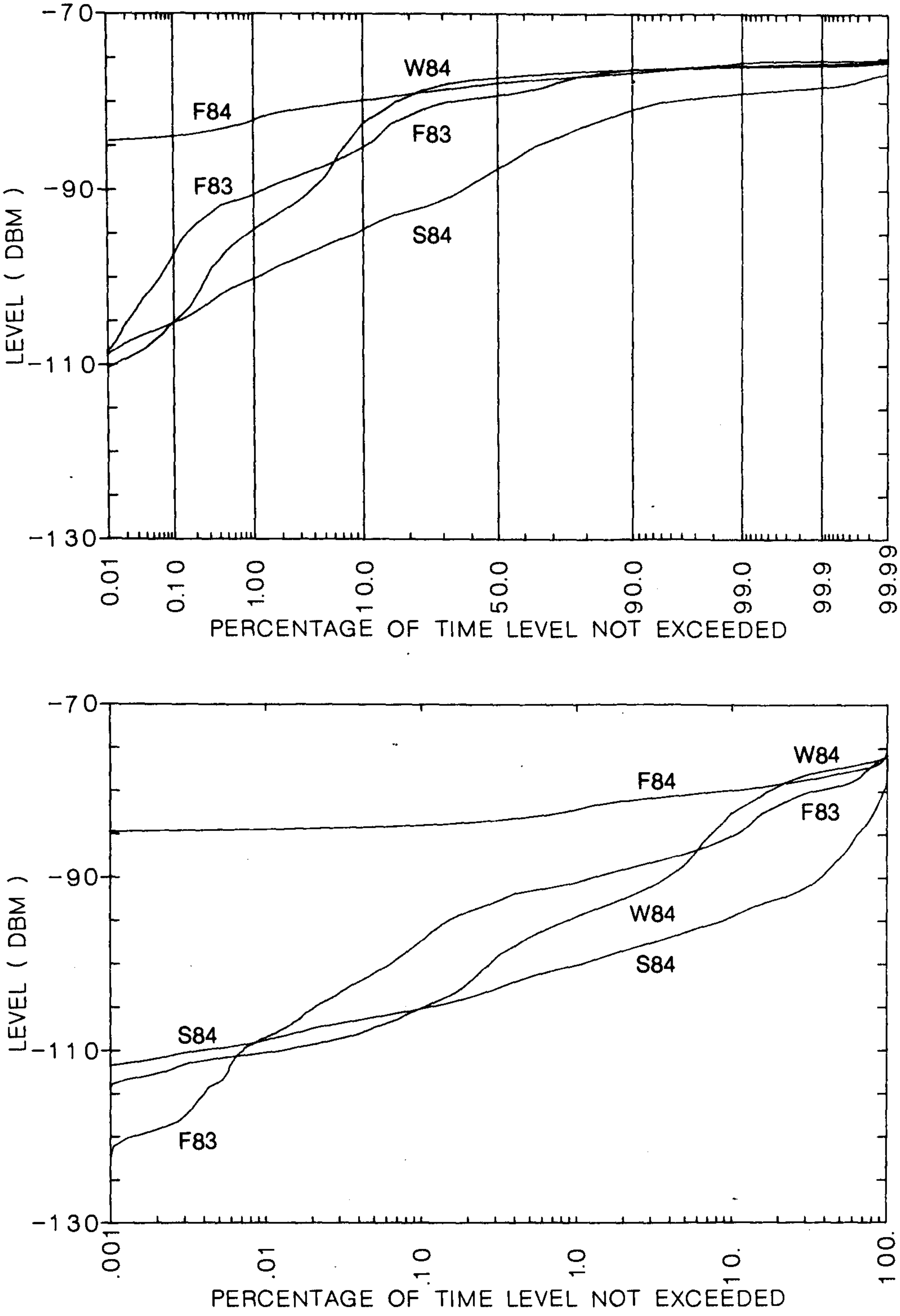


Figure 10: Seasonal statistics, Lowther Peak to Martyr Peak.
F83: Sept-Dec 1983; W84: Jan-Apr 1984;
S84: June-Aug 1984; F84: Sept-Dec 1984.
Upper: Log-normal; Lower: Log-log.

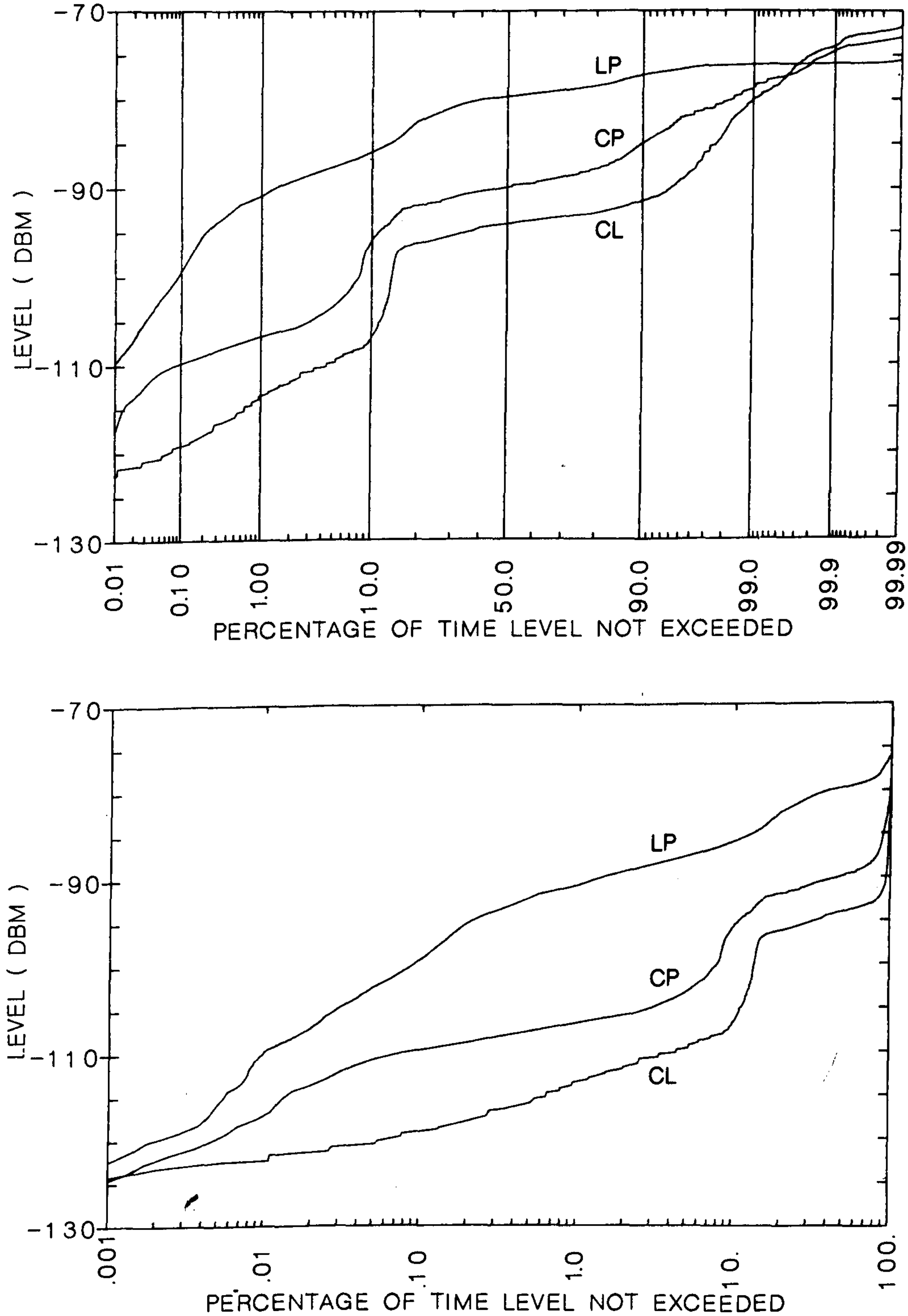


Figure 11: Seasonal statistics on UHF paths, Sept-Nov 1983. LP: Lowther Peak - Martyr Peak; CP: Cockburn Peak - Lowther Peak; CL: Cockburn Lake - Lowther Peak. Upper: Log-normal; Lower: Log-log.

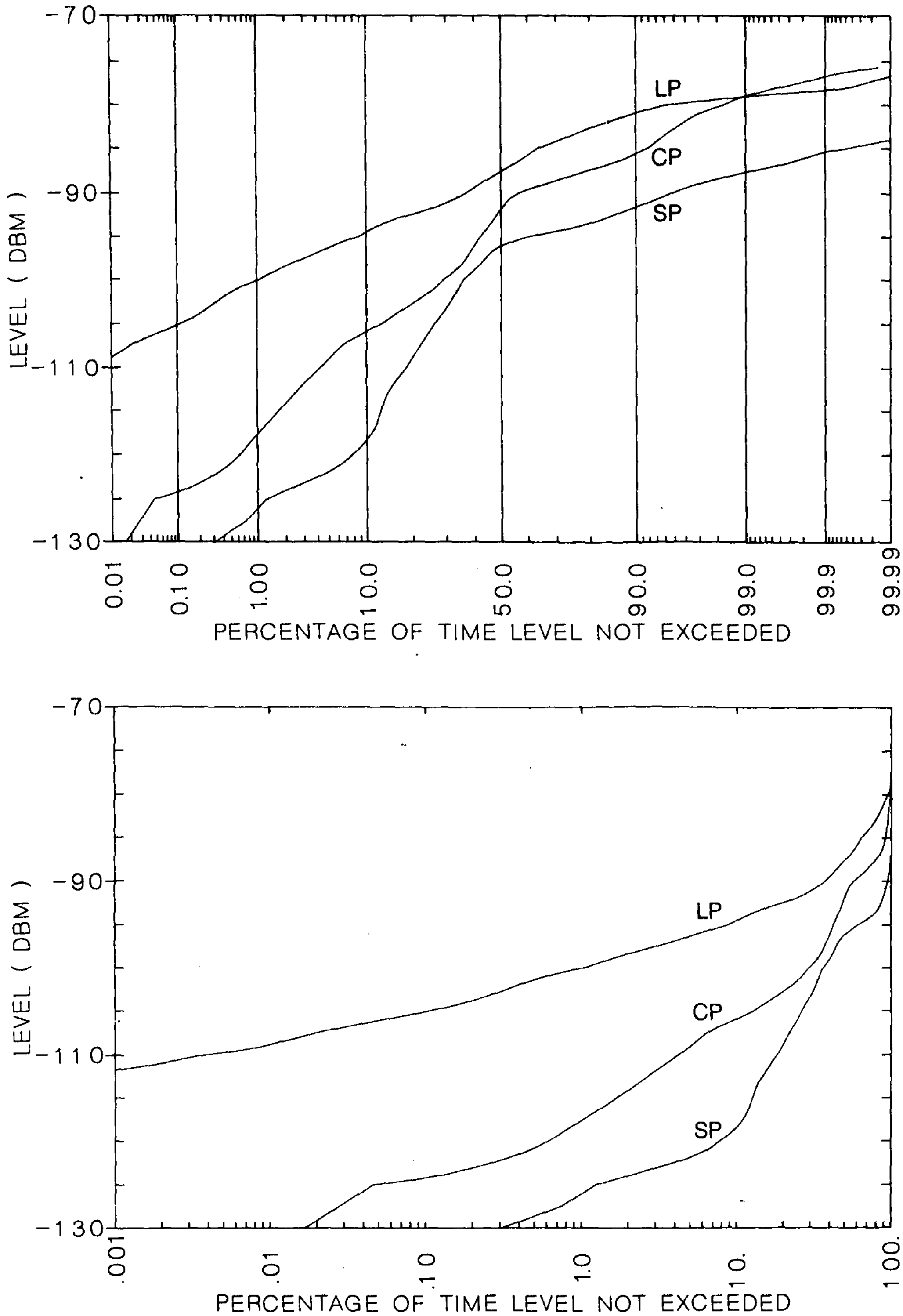


Figure 12: Seasonal statistics on UHF paths, Jun-Aug 1984. LP: Lowther Peak - Martyr Peak; CP: Cockburn Peak - Lowther Peak; SP: Schomberg Peak - Cockburn Peak. Upper: Log-normal; Lower: Log-log.

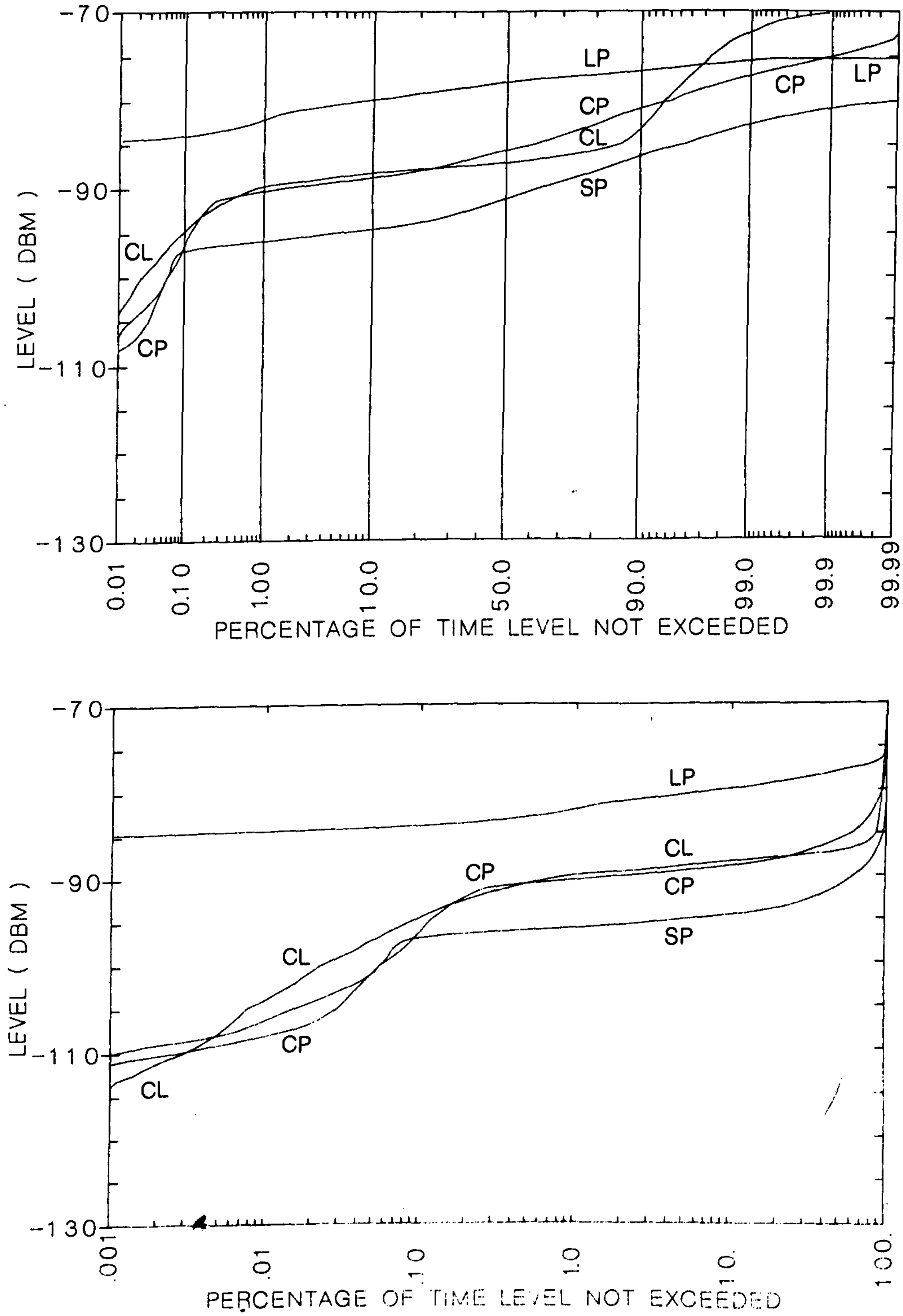


Figure 13: Seasonal statistics on UHF paths, Sept-Dec 1984.
LP: Lowther Peak - Martyr Peak; CP: Cockburn Peak - Lowther Peak; CL: Cockburn Lake - Lowther Peak; SP: Schomberg Peak - Cockburn Peak.
Upper: Log-normal; Lower: Log-log.

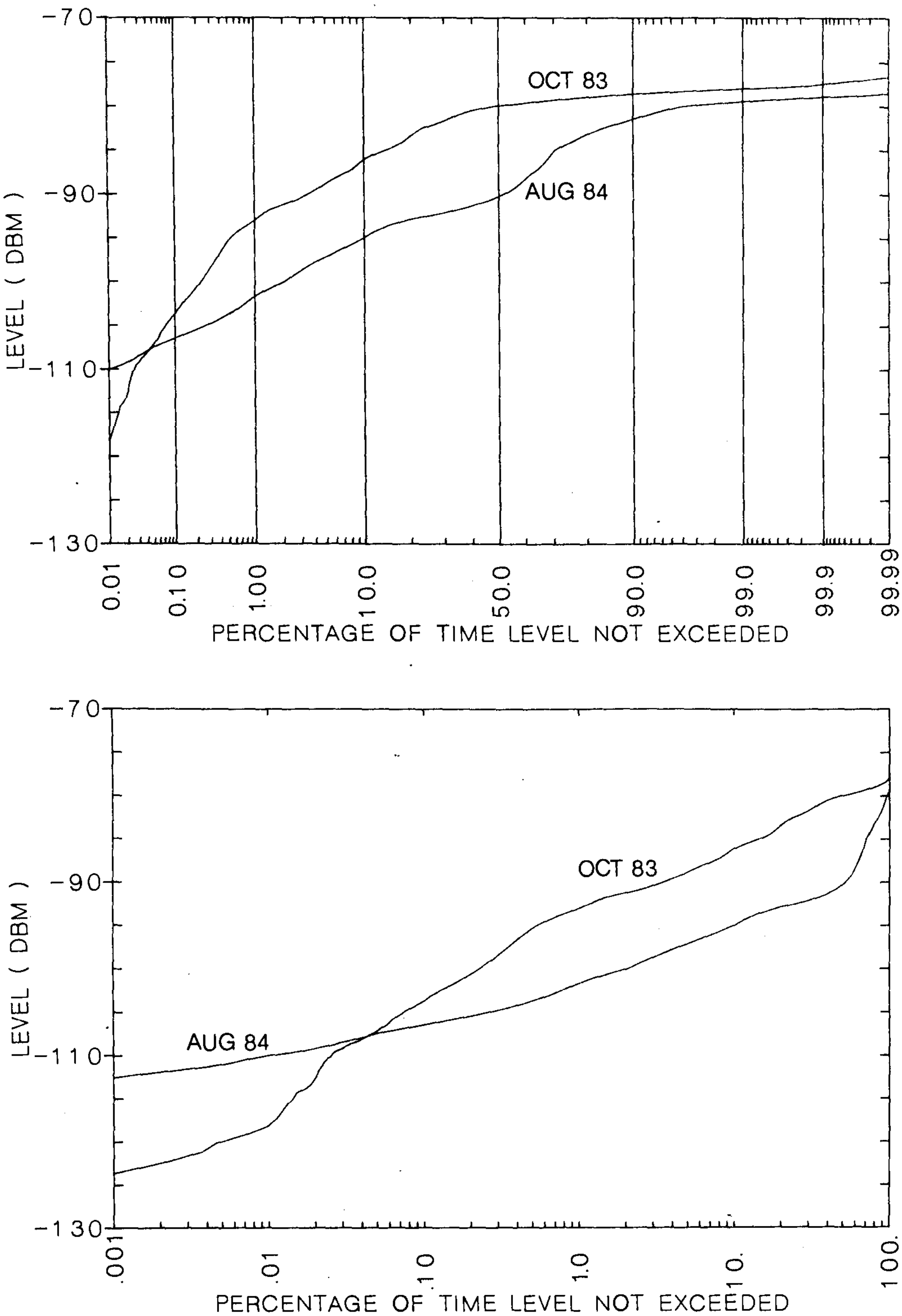


Figure 14: Worst month statistics, Lowther Peak to Martyr Peak. Upper: Log-normal; Lower: Log-log.

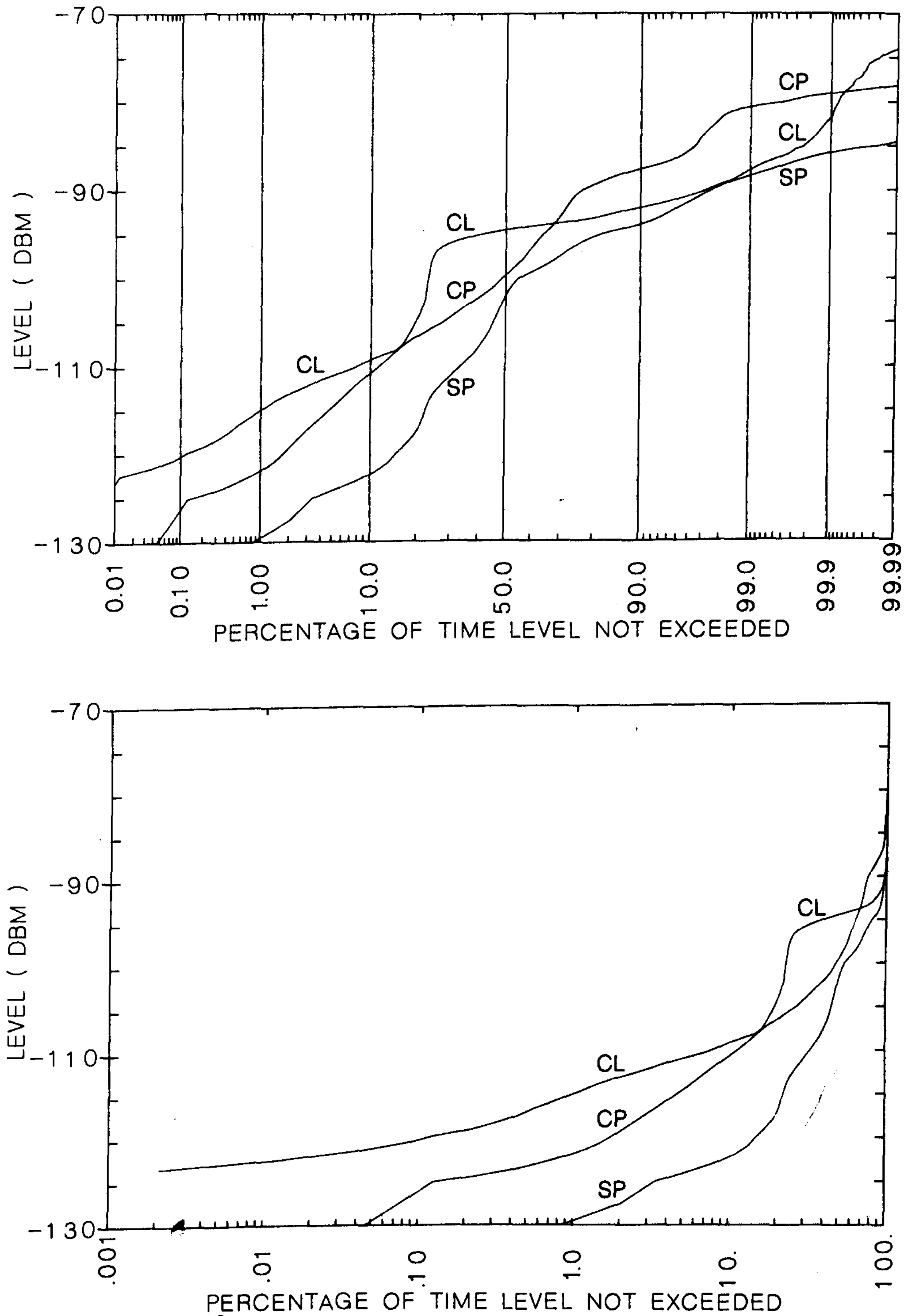


Figure 15: Worst-month statistics on UHF paths. CP: Cockburn Peak - Lowther Peak, Jul 1984; CL: Cockburn Lake - Lowther Peak, Sept 1983; SP: Schomberg Peak - Cockburn Peak, Jul 1984. Upper: Log-normal; Lower: Log-log.

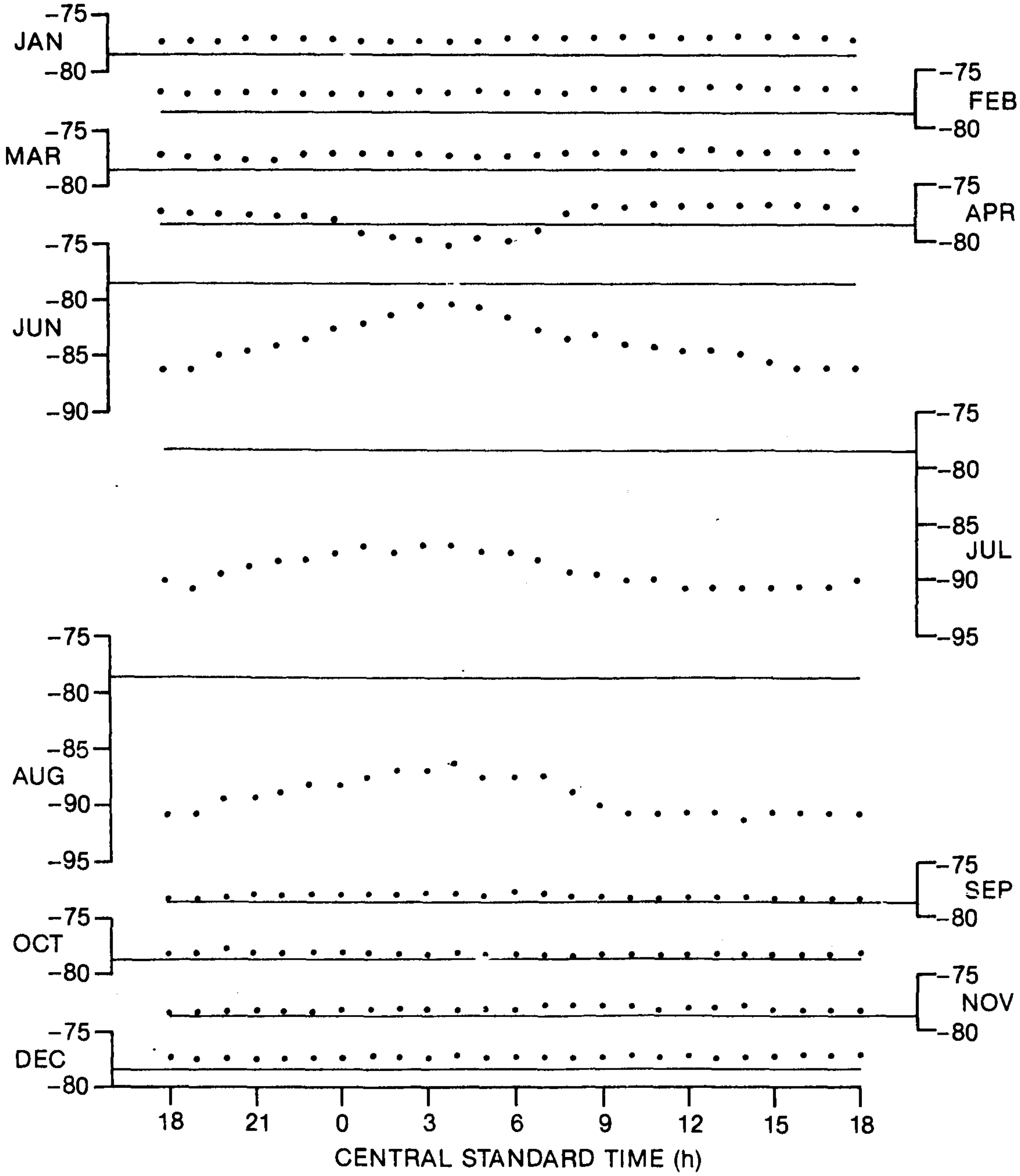


Figure 16: Diurnal variations of median signal level, Lowther Peak - Martyr Peak, 1984.

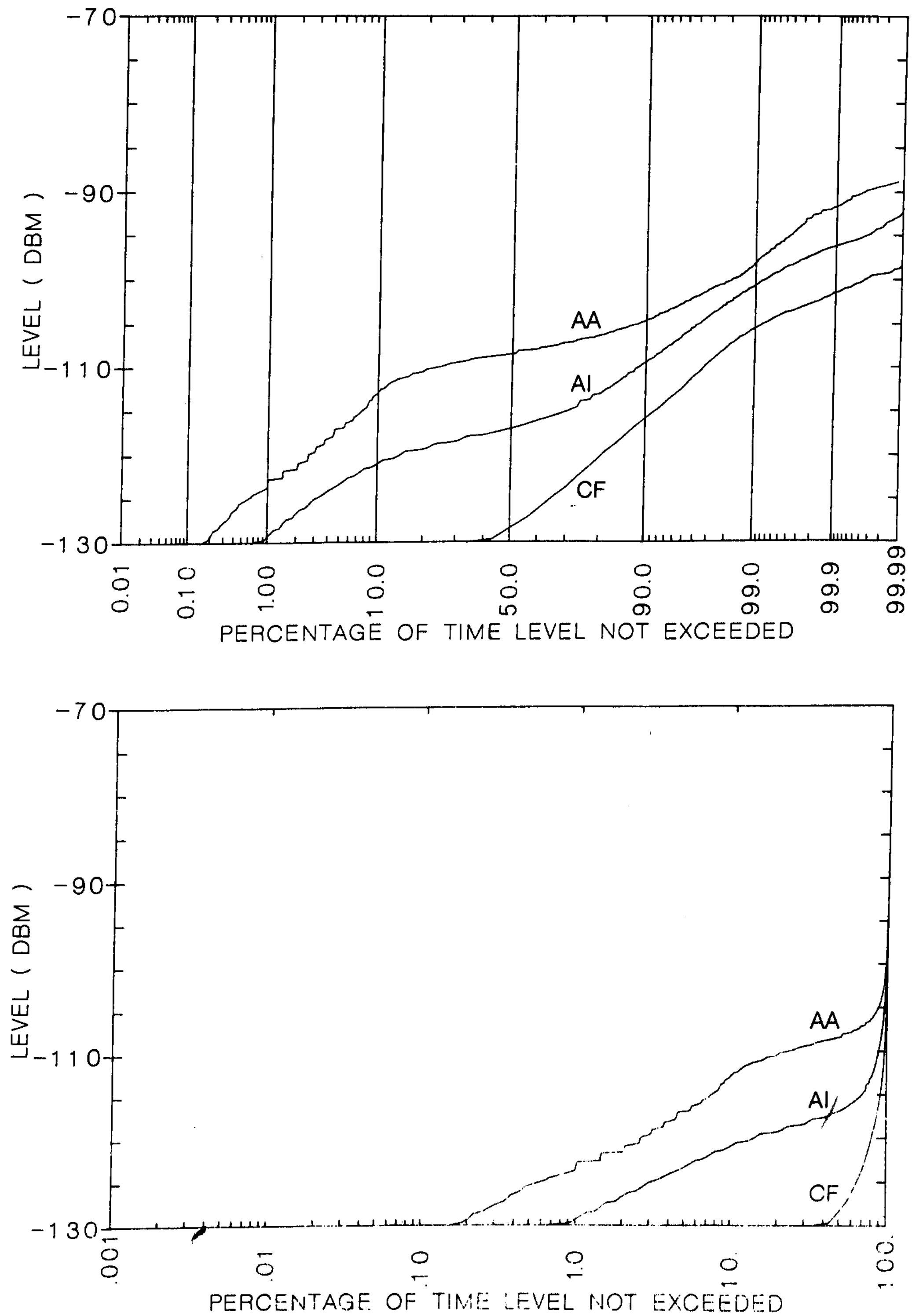


Figure 17: Seasonal statistics on VHF paths to Lowther Beach, Sept-Nov 1983. AA: Acland Acres; AI: Allison Inlet; CF: Cockburn Flats.
Upper: Log-normal; Lower: Log-log.

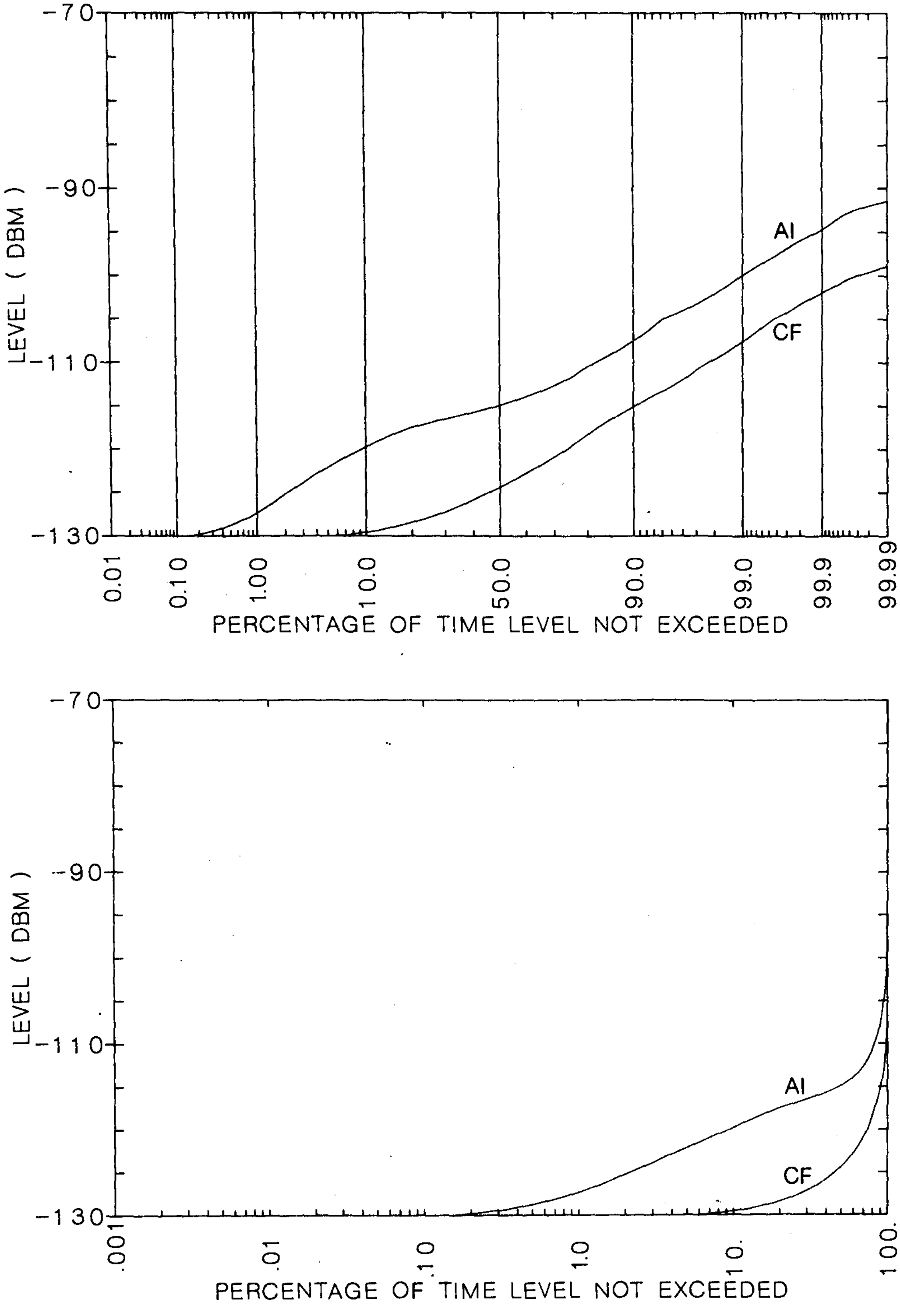


Figure 18: Seasonal statistics on VHF paths to Lowther Beach, Jun-Aug 1984. AI: Allison Inlet; CF: Cockburn Flats. Upper: Log-normal; Lower: Log-log.

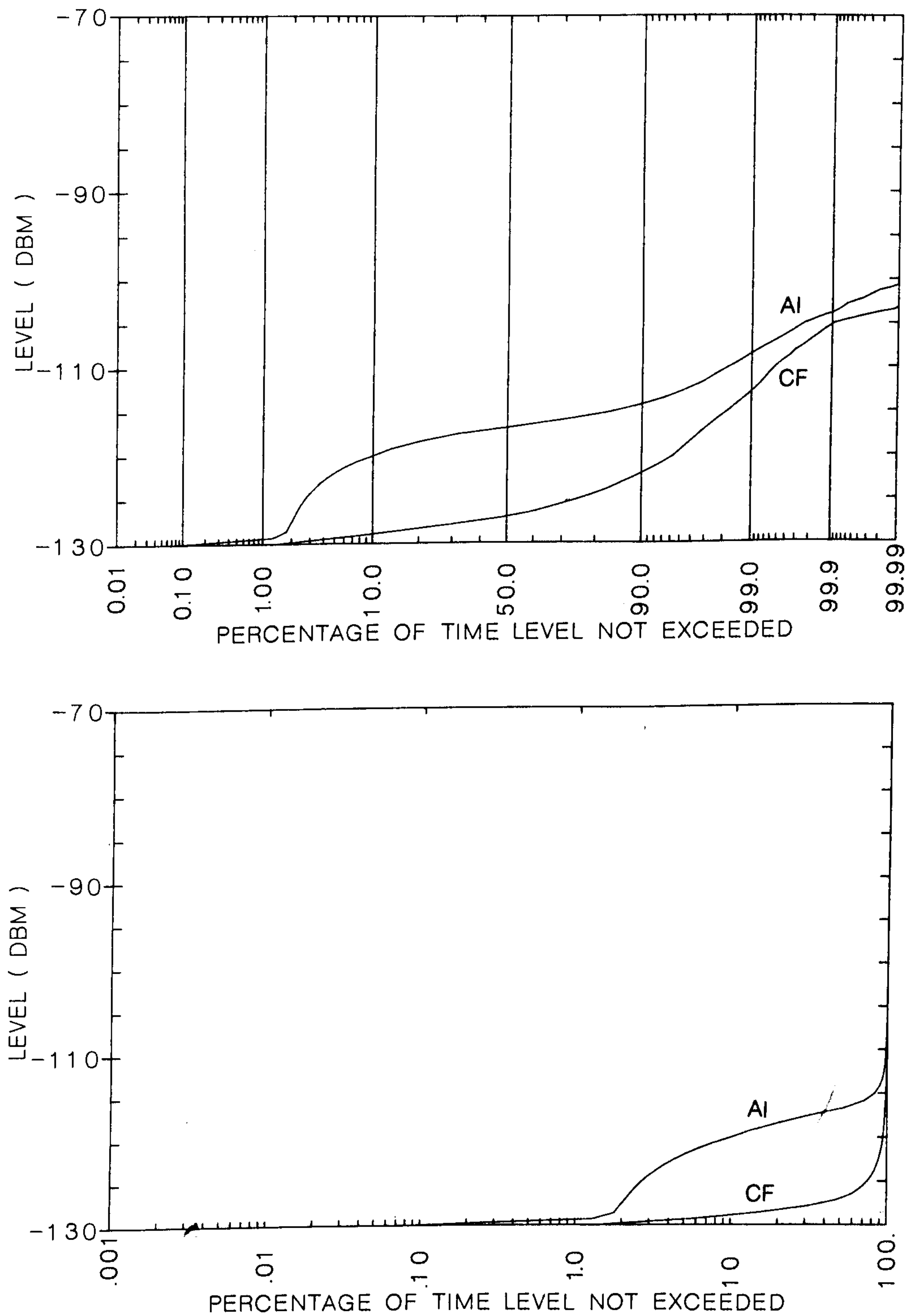
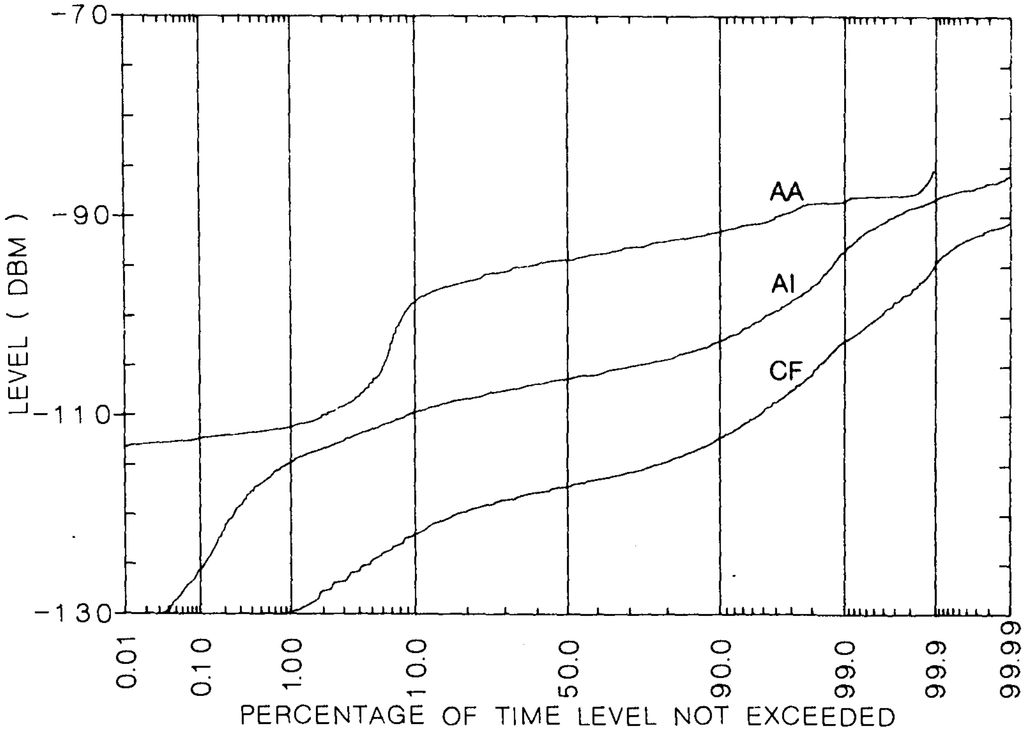


Figure 19: Seasonal statistics on VHF paths to Lowther Beach, Sept-Oct 1984. AI: Allison Inlet; CF: Cockburn Flats. Upper: Log-normal; Lower: Log-log.



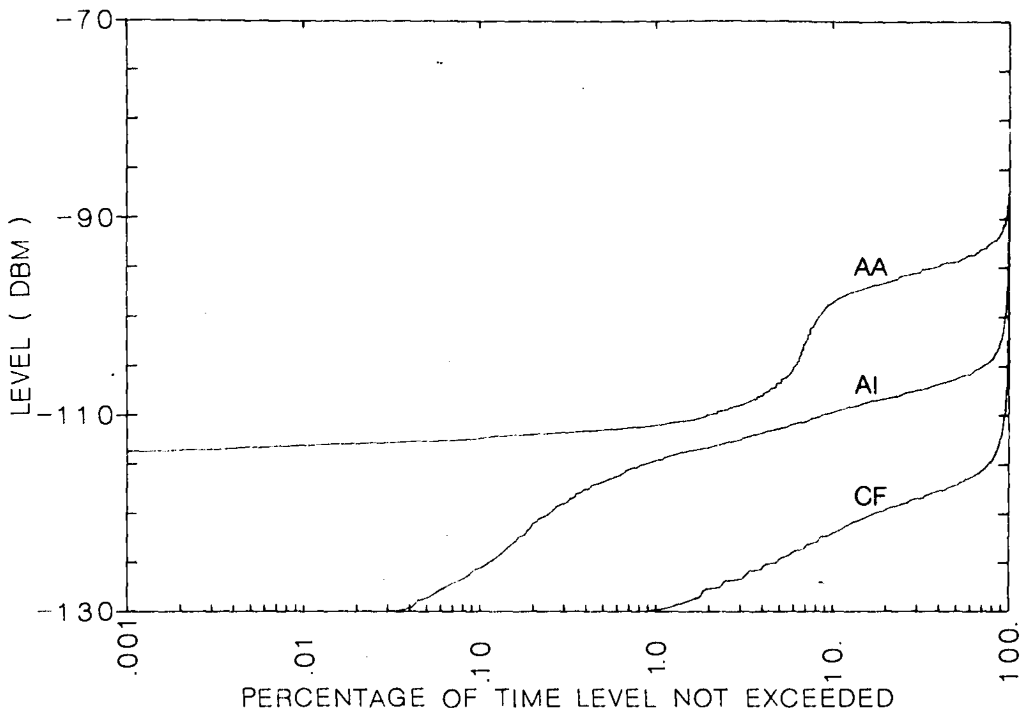


Figure 20: Seasonal statistics on VHF paths to Lowther Terrace, Sept-Nov 1983. AA: Acland Acres; AI: Allison Inlet; CF: Cockburn Flats.
Upper: Log-normal; Lower: Log-log.

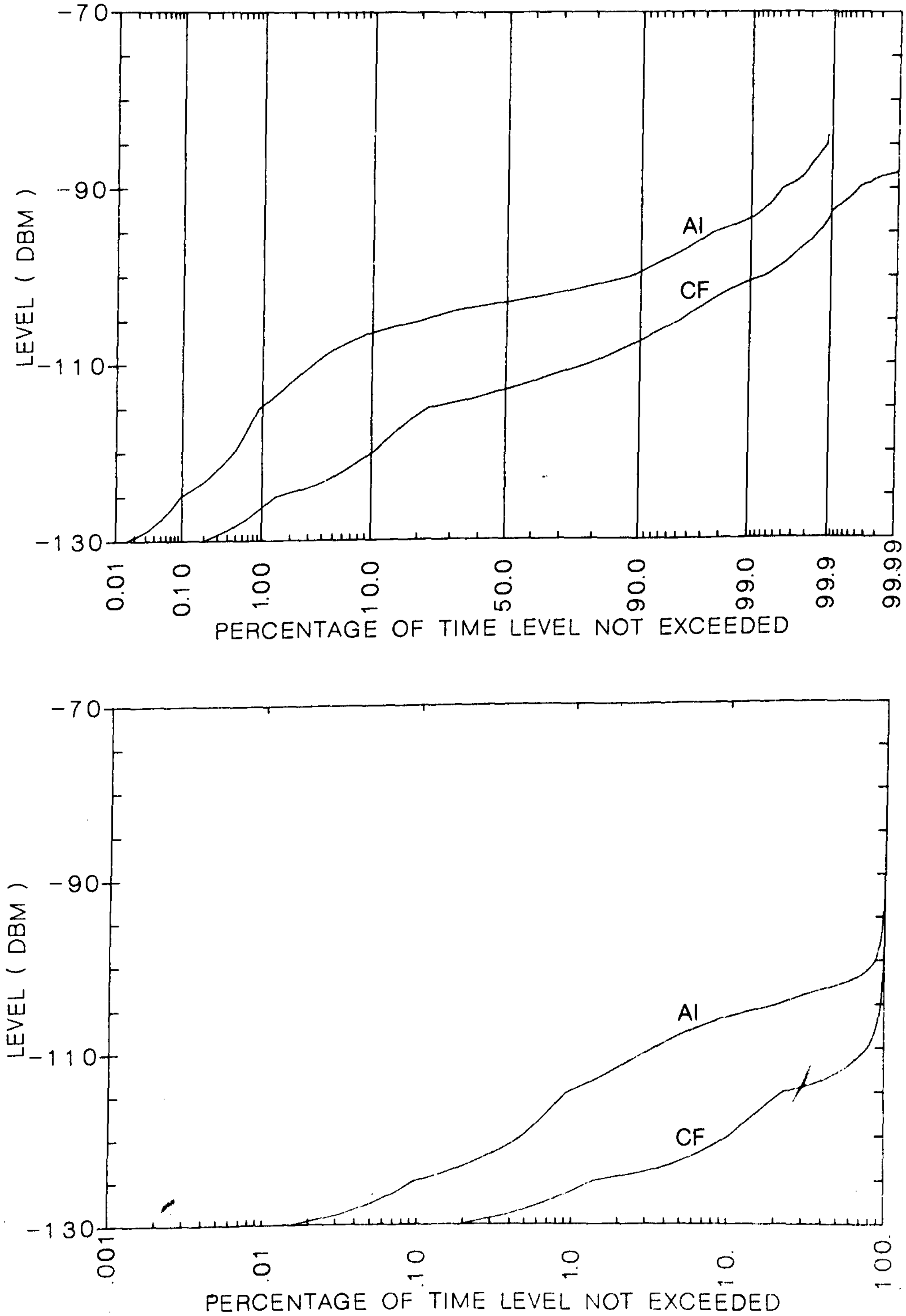


Figure 21: Seasonal statistics on VHF paths to Lowther Terrace, Jun-Aug 1984. AI: Allison Inlet; CF: Cockburn Flats. Upper: Log-normal; Lower: Log-log.

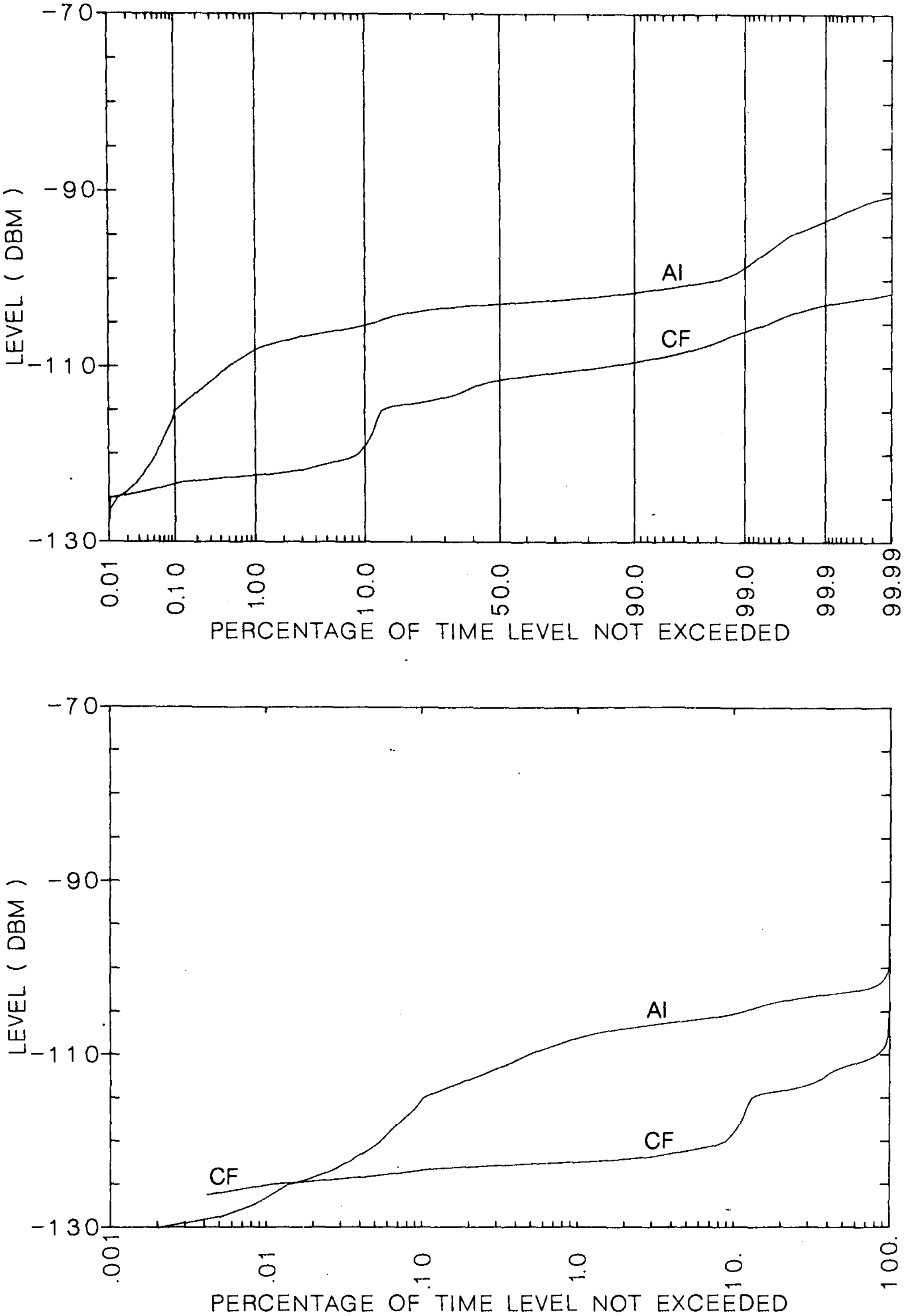


Figure 22: Seasonal statistics on VHF paths to Lowther Terrace, Sept-Dec 1984. AI: Allison Inlet; CF: Cockburn Flats. Upper: Log-normal; Lower: Log-log.

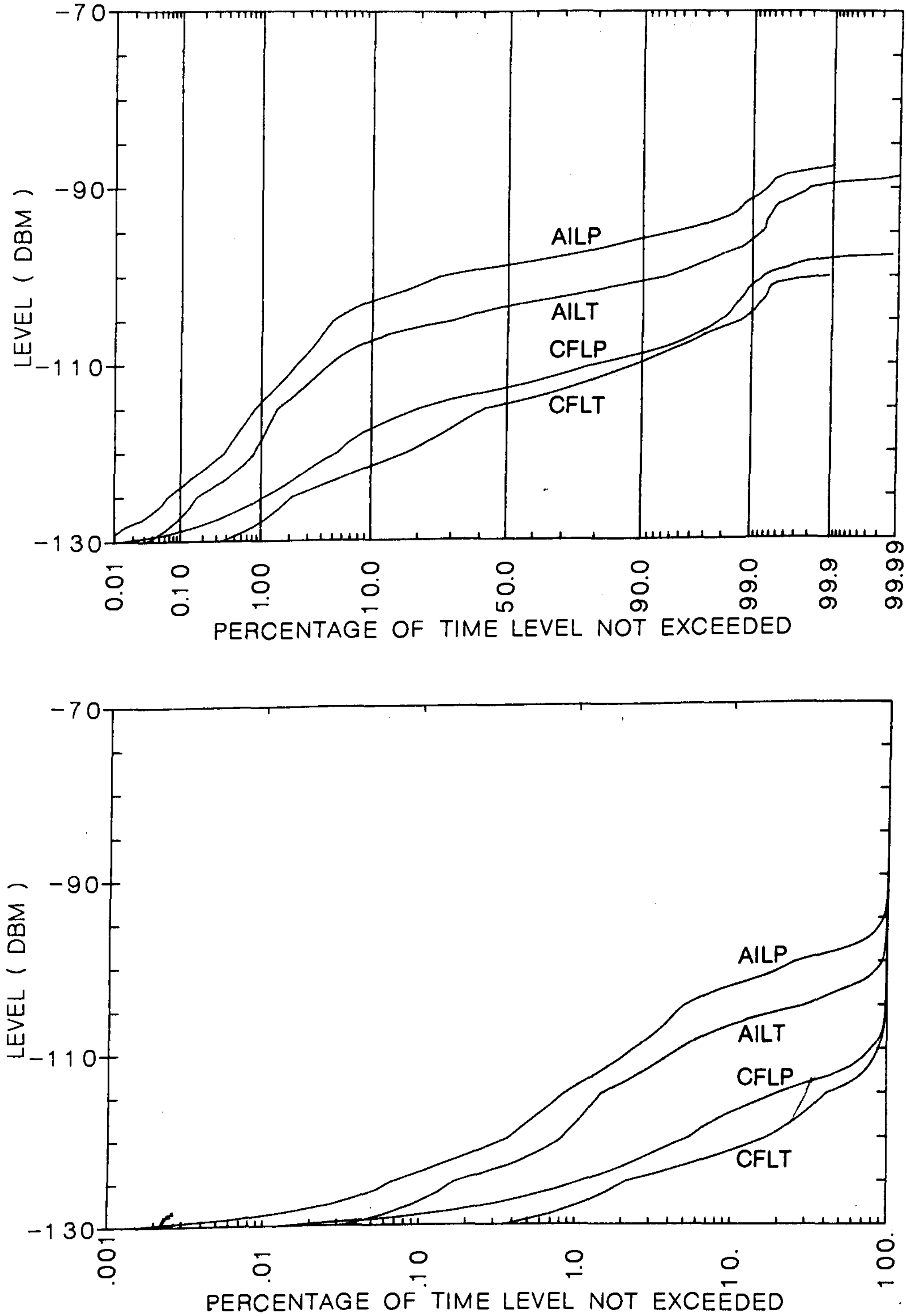


Figure 23: Comparison of statistics on VHF paths to Lowther Peak and Lowther Terrace, mid-July, 1984. AI: Allison Inlet; CF: Cockburn Flats; LT: Lowther Terrace; LP: Lowther Peak. Upper: Log-normal; Lower: Log-log.

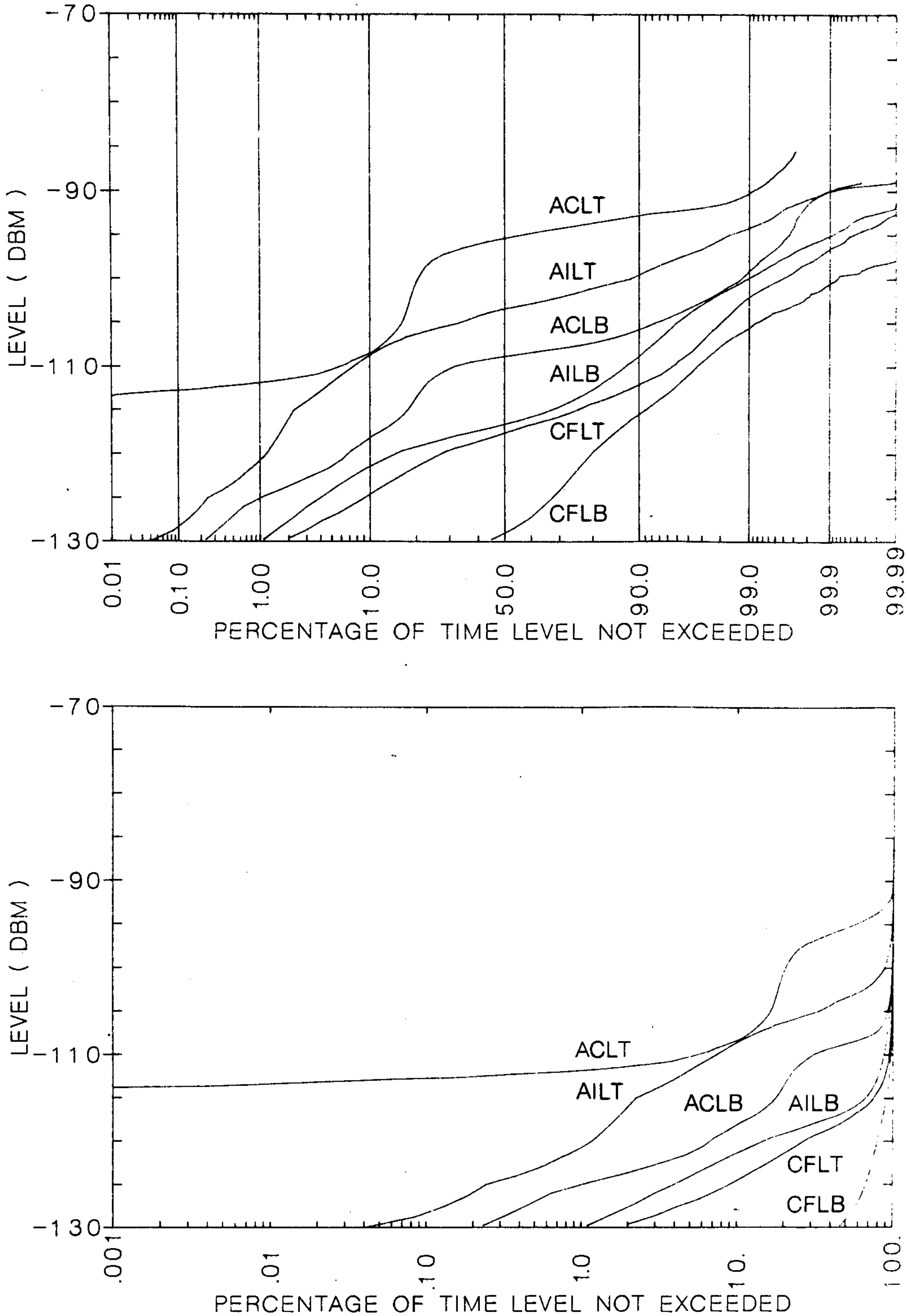


Figure 24: Worst-month statistics on VHF paths. AC: Acland Acres; AI: Allison Inlet; CF: Cockburn Flats; LT: Lowther Terrace; LB: Lowther Beach.
Upper: Log-normal; Lower: Log-log.