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HF/VHF RADIOWAVE TECHNIQUES FOR INVESTIGATING HIGH LATITUDE IONOSPHERIC DISTURBANCES

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13. ABSTRACT (Maximum 200 words)

The object of this three year contract was to develop a unified model for radio wave propagation in the 2 - 147 MHz band at high latitudes, especially during disturbances. This particularly included the analysis and measurement of the frequency dependence during polar cap absorption events and assessment of the effects of artificially induced perturbations on radio waves within this band. This project concentrated on single hop HF ionospheric propagation in the 2 - 30 MHz band and VHF meteor scatter in the 45 - 147 MHz band.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

1.0 INTRODUCTION

The object of this three year contract was to develop a unified model for radio wave propagation in the 2 - 147 MHz band at high latitudes, especially during disturbances. This particularly included the analysis and measurement of the frequency dependence during polar cap absorption events and assessment of the effects of artificially induced perturbations on radio waves within this band. This project concentrated on single hop HF ionospheric propagation in the 2 - 30 MHz band and VHF meteor scatter in the 45 - 147 MHz band.

This final report summarizes the work accomplished during the three year contract. Several broad objectives comprise the major portion of the work performed under this contract. These areas include:

- Development of a digital meteor scatter receive system for operation at Thule AB, Greenland.

- Development of analysis techniques for the assessment of natural ionospheric radio wave absorption from the low HF through mid VHF frequencies.

- Establishment of quiet time baselines for the polar cap propagation of High (2-30MHz) and Very High (30 - 300 MHz) Frequency radio waves.

- Development of a broad frequency range assessment of non-deviative ionospheric absorption during quiet and disturbed times. Primary emphasis given to characterizing absorption during polar cap absorption events that occurred during the ascending side of solar cycle number 22 (1988 - 1989).

- Studies and experiments aimed toward the definition of a latitude dependence for oblique ionospheric modification by high frequency radio waves.

A summary of these tasks are provided in the following sections.

2.0 SCOPE OF WORK

The broad objectives under this contract can be categorized into three general areas of research: general engineering support for the maintenance and expansion of the Greenland High Latitude Meteor Link Test Bed; data analysis of the Greenland High Latitude Test Bed database covering both disturbed and quiet times; and the development of instrumentation for the analysis of artificial ionospheric disturbances.

2.1 Greenland High Latitude Meteor Link Test Bed General Engineering Support

At the contract start, the Greenland High Latitude Test Bed consisted of a single link of 1210 km between Sondrestrom-Thule with the transmitter sited at Sondrestrom and the receiver sited at Thule. During the summer of 1989 a second link of 690 km was established between Sondrestrom and Narsarsuaq with a second transmitter sited at Sondrestrom and a receiver sited at Narsarsuaq. Work conducted on these two links is presented in the following paragraphs.

2.1.1 Sondrestrom-Thule Link

While this link had been operating for some time prior to this contract, engineering improvements were required for improving the link reliability and obtaining the systems status. A listing of these improvements includes:

- Replacement of the Interdyne tape deck by a more reliable Kennedy 6455 cartridge tape drive using a 20 Mbyte tape cartridge (DC-600) at the Thule site..

- Improvement of internal noise generated by the a DC switching power converter within the receiver chassis. The receiver in Thule was experiencing internal 35 MHz noise. Through several filtering attempts, this interference was reduced to acceptable limits. Noise measurements made indicated that additional interference was being generated outside the system. During the latter months of 1988, a new shelter was erected for the Thule system of sufficient size for all equipments and personnel with new power and phone lines installed. Noise measurements made at the new location still indicated this interference on all channels. This interference was subsequently traced to a local FM radio station and a 137 kHz transmitter located on North Mountain. A prototype filter was designed, built and tested and found to reduce the interference to acceptable limits.

- The Thule receive system software was updated in March 1988 for the purpose of implementing a remote diagnostic routine. This routine allowed a remote user to poll the receive system to determine the status of the recording tape, insight into system malfunctions or the occurrence of a polar cap absorption event. In addition, the software was updated to reduce or eliminate the recording dead time between successive meteor trails to zero.

- During July 1988 new calibration and operating software was installed in the Thule receive system to accommodate the dual polarization measurements. The operating system software provided for real time, simultaneous display of the vertical and horizontal channels.

- For improved synchronization between Sondrestrom-Thule, a satellite clock was installed at the Thule site in October 1988. The receive system software was updated to interrogate the satellite clock every two hours and to synchronize the receive system to within one second accuracy.

- During a visit to the Thule site in March 1989, the Turbo Pascal compiler was updated from version 3 to version 4 for the purpose of extending the previous 64 kbyte execution code limit and to increase the program execution speed. To accomplish this upgrade, modules written in assembly required minor changes while major changes were required to the main program and the software driver for the MetraByte Dash-16 data acquisition card.

- During a visit to the Thule site in December 1989/January 1990, new acquisition software was implemented for improved storage of system noise information. In addition, a narrow band riometer was installed at the Thule site with a bandwidth of 30 kHz.

- During April 1990 a campaign was conducted to investigate fast fading and frequency diversity on the meteor scatter channel. To conduct this campaign two spare meteor scatter receivers were modified with synchronous detectors with 1,000 Hz bandwidths and special control cables manufactured to enable these two receivers to be controlled by one computer. On completion of the campaign, the additional receivers were removed and transferred to Narsarsuaq for an identical experiment in July 1990 and the system configured to its pre-April set-up.

2.1.2 Sondrestrom-Narsarsuaq Link

This link was established during the summer of 1989 operating on four frequencies of 45, 65, 85 and 104 MHz. This link remained in operation for a one year period and was dismantled during the third quarter of 1990.

The link transmit system was deployed in Sondrestrom adjacent to the transmit system for the Sondrestrom-Thule link. Horizontally polarized yagi antennas are used for transmitting on the four frequencies. In addition, vertical whip antennas are erected for additional vertical polarized transmissions on 65 and 104 MHz.

The link receive system was deployed at Narsarsuaq configured the same as the Thule receive system. The receive antennas are crossed yagi antennas. Interference problems were originally detected on the 45 and 104 MHz channels. The 45 MHz interference was determined to be induced mainly by the Zenith Z-248 computer, Kennedy tape drive and the satellite clock. Rearrangement of these three components reduced this interference to acceptable levels. The 104 MHz interference was found to be coupling between the 65 and 104 MHz antennas. Installing a PVC instead of steel mast for the 104 MHz antenna reduced the noise floor to within acceptable levels.

During the duration of operation of the link, a minimal amount of engineering support was required to support the system. However, a concerted effort was expended in obtaining a detailed knowledge of the Sondrestrom antenna patterns over an uneven foreground that cannot be analyzed by NEC. This effort maintained applicability to both of the links. A special program was developed that accepted foreground profiles and free space antenna radiation patterns. As expected, the terrain in the vicinity of the antenna towers had a marked influence on the radiation patterns. As a result of these findings, the transmit antennas were rearranged in July 1990 to compensate for these findings.

During July 1990 a campaign similar to the April 1990 campaign using the Sondrestrom-Thule link was conducted. In addition, experiments were conducted during this campaign to compare the performance of vertical monopole antennas and horizontal and vertical yagi antennas.

At the end of October 1990 a short campaign to support Navy activities was carried out and all meteor scatter equipment associated with the Sondrestrom-Narsarsuaq link was dismantled and shipped to AFSC/GL Hanscom AFB at the conclusion of this campaign.

2.2 Greenland High Latitude Meteor Scatter Test Bed Data Analysis

Over the performance of the three year contract a substantial amount of data was collected as part of the meteor scatter database for both the Sondrestrom-Thule link as well as for the Sondrestrom-Narsarsuaq link.

Data from the High Latitude Meteor Scatter Test Bed acquisition system consists of five second records of 500 received signal power measurements from the horizontally polarized channel, 500 received power measurements from the vertically polarized channel and 500 measurements of the phase of the vertical channel relative to the horizontal channel. A 20 item header consisting of the date, time, noise level, transmit power, frequency, and other information is attached to each 1,500 (500x3) point data record. The presence of a 400 Hz FM signature is used to differentiate signal from noise bursts and is indicated by the sign of the phase channel (negative indicates presence of phase channel). Data is logged continuously in 5 second records; however, only those records in which the 400 Hz tone is detected are transferred to the tape cartridges.

Data from these tape cartridges are transferred to the AFSC/GL VAX computer.

The next step in the analysis procedure is classification in which the dominant propagation mechanism in each data record or sequence of records is identified. If the dominant mechanism is meteor, the type of each meteor trail in the record or sequence of records (underdense or overdense) is identified and entered into the header along with the beginning of the trail and its duration. During the classification procedure, a screening is made for records in which noise spikes have occurred and for data transfer errors; these records are discarded.

After classification, the next step is to statistically analyze the data. This is accomplished to create a database of key statistics which represent the important information. This database can then be queried in a number of different ways to extract the required information. Statistical analysis is divided into two general categories: propagation analysis and communication analysis.

Propagation statistics allow analysis of the arrival rate of trails, their duration and duty cycle as a function of trail type, signal level, time of day, day and frequency. These statistics can be used to determine the effect of polar cap absorption and to calibrate astronomical type prediction models.

Communication statistics allow a user to infer the performance of a specified link from the actual data. Parameters that can be identified by the user are the data rate, modulation, error rate, packet structure and signalling protocol. Users can specify either a fixed data rate system or an adaptive rate system. Available statistics include time to deliver a message and throughput as a function of the time of day, event type (underdense, overdense or sporadic-E), frequency, data rate, packet duration, error rate and packet structure.

From these two categories, seven standard databases are developed: Number of arrivals exceeding a threshold; Time above a threshold; Distribution of trail durations; Fading statistics; Noise and link history statistics; and Underdense decay time constants. In addition a special database was constructed covering fading properties of meteor trail returns in support of the three campaigns conducted at Thule and Narsarsuaq in 1990. Access is available to all of these various databases for the purpose of editing or presenting the data in various ways.

Database construction has been conducted on the Sondrestrom-Thule link since the contract start and the Sondrestrom-Narsarsuaq link since the summer of 1989. The routine operation and analysis provided the quiettime baseline from which disturbances were to be evaluated. As significant polar cap absorption effects are observed when the path is in sunlight, the first significant observation was observed during the Boreal summer 1989. Results of the analysis of these PCA events was presented at the annual meeting with the Commission for Scientific Research in Greenland held in Copenhagen in April 1990; the IES Conference in Springfield, VA in May 1990; the MILCOM Conference in San Diego, CA in October 1990.

Further reporting and presentation of the data analysis results are listed in Section 4.0, Presentations and Publications.

2.3 Instrumentation for the Analysis of Artificial Ionospheric Disturbances

The polar cap region occasionally experiences short-wave radio blackouts due to solar bursts which create extraordinarily dense ionization at low altitudes in the D-region of the ionosphere (40 to 80 km). This phenomenon indicates that perhaps at some power level a high HF or VHF frequency might provide connectivity at times when conventional HF systems are experiencing blackout. Under this task, instrumentation was developed, designated as the HF Channel Probe, which is capable of measuring the relatively weak HF signal available during a PCA, such that intelligent comparisons and trade-offs can be made when designing communication systems for the polar cap regions. An important requirement of this instrument is to measure the received signal amplitude, Doppler shift and angle of arrival from the Channel Probe transmitters during special ionospheric modification experiments. These experiments utilize the Voice of America (VOA) transmitter in Delano, California to artificially create changes in the structure of the ionosphere at the 1-hop F-region midpoint. High Doppler resolution and angle of arrival measurement capability is part of the HF probe system to meet its mission requirements. Conducting preliminary experiments in the Southwestern United States alleviates the costly requirement for deployment to the Arctic region for experimentation.

The HF Channel Probe receive system is based on three RACAL 6790 communication receivers and a Zenith 248 AT computer. A multi-channel signal digitizer is used to convert the analog receiver outputs to digital sample records. A digital signal processor is added to the computer to pre-process the raw data so as to reduce the volume of recorded data to a manageable level and to allow on-site display of the amplitude and angle of arrival of the received signal. The control display and storage functions of the system are provided by a C language program. Interfaces to the digitizer and digital signal processing boards are accomplished by subroutine calls from C to assembly language drivers. The system is configured with three short monopole antennas in an "L" configuration. The HF Channel Probe transmit system consists of a PTS 40 frequency synthesizer, ENI 150 watt power amplifier and a sloping "V" transmit antenna.

Two campaigns were conducted using the HF Channel Probe in association with the VOA transmitter. The Probe reference signal, used the Probe transmitter, and was located at the VOA high power transmit site in Delano, California. The Probe receive system was established at Barksdale AFB, Louisiana. Separation of the transmit and receive systems was ≈2,400 km. The first campaign in January 1990 was conducted under a separate AFSC/GL contract. The second campaign in September 1990 was conducted under this contract for a duration of five days. During both campaigns a Digisonde 256 was operated at the mid-point, Kirtland AFB, New Mexico for the purpose of performing propagation management.

In support of the second campaign, several modifications were carried out on the Probe system. The most significant modification to the system was the software to include several new modes of operation which allow for the use of higher sampling rates making it possible to provide wider unaliased Doppler spectra which include higher frequency fading components. Another modification was to include a fourth channel in the Probe system, similar to the three for the actual Probe signals, to receive and record the VOA signals in exactly the same format including the spectrum analysis. Step attenuators (10 dB per step) were added at the input to each channel to allow specific changes in the signal amplitudes going into each receiver, so as to avoid saturation. Results of this campaign are presented under separate cover as reflected in Section 4.0.

3.0 SUMMARIES AND CONCLUSIONS

3.1 Greenland High Latitude Meteor Scatter Test Bed

3.1.1 Sondrestrom-Thule Link

The Test Bed transmitting site is located to the south of Sondrestrom AB on Black Ridge at an altitude of 200 m. The transmitters are housed in a small building and the antenna tower is located approximately 10 meters from the end of the building.

The transmitting antennas for the link to Thule AB, one for each of the operational frequencies (35, 45, 65, 85, 104 and 147 MHz), are mounted on the tower structure at a height of approximately 1.5 wavelengths. The antennas for 35 through 104 MHz are five-element Yagis and the 147 MHz is a fourteen-element Yagi. All the antennas are mounted to radiate horizontally polarized signals. All use a gamma matched low-loss Heliax© coaxial feed line.

The effective radiation pattern of an elevated antenna is determined by the directional properties of the antenna itself, and by the influence of the terrain in front of it. If the foreground is perfectly flat, it can be shown that the antennas should be placed 1.5 wavelengths above the ground to obtain the best radiation pattern for a 1200 km meteor scatter link. Further, for a perfectly reflecting foreground this would produce a desirable 6 dB enhancement of the EIRP at an elevation angle of approximately 8 degrees.

However, the foreground terrain at Sondrestrom AB is not flat, and the surface consists of bedrock with a thin layer of gravel, grass and brush on top. The permittivity of the ground is estimated to be 2 to 3 throughout the year, while the conductivity is less than 0.0001 S/m. This means that the reflection coefficient of the terrain will be somewhat less than unity, but still the reflections from the ground will significantly modify the antenna radiation patterns.

An uneven ground terrain can block ground reflection and entirely restrict the propagation of electromagnetic wave at certain azimuth and elevation angles. The popular antenna simulation program "Numerical Electromagnetics Code (NEC)" has only limited capabilities in modeling an uneven terrain. Thus, a computer program has been developed to investigate the effective radiation pattern of an antenna over an arbitrary ground terrain.

The computer program requires the inputs of the free-space antenna radiation pattern and the digitized ground profile. The free-space patterns of the Yagi antennas can be generated by the NEC program while the ground profiles of the Thule, Sondrestrom and Narsarsuaq sites are developed using corresponding contour maps.

Each ground terrain is digitized every 10 degrees of azimuth to develop a piecewise linear ground profile. The near foreground terrain has been modeled in more detail than the more distant features, since it not only restricts the blocking angle but significantly affects the ground reflection, whereas distant mountain ranges only influence the blocking angle.

The predominant features of the foreground terrain are the steep mountain approximately 3 km to the far side of the valley, the small hill right in front of the antenna tower, and a gently sloping terrain leading from the small hill into the valley.

The first feature restricts the possible elevation angle to values greater than 1.8 to 2.2 degrees over the azimuthal extent of the antenna beam, and the other features significantly influence the antenna radiation patterns as discussed below. The above mentioned computer program has been used to calculate the effective radiation patterns for four of the transmitting antennas.

The small hill in front of the antenna tower prevents ground reflections at elevation angles up to 20 degrees for the 65, 85, and 104 MHz antennas. The presence of the hill eliminates the null otherwise to be expected at the horizon, and it also eliminates the up to 6 dB extra antenna gain which would have been present at an elevation angle of approximately 8 degrees if the antennas were mounted 1.5 wavelengths above a flat foreground.

The receiving site is situated on South Mountain, a ridge south of Thule AB at an elevation of 240 m. The receiver, is housed in a shielded, thermostat controlled, box mounted to the tower structure in a position suited to minimum length feed lines from each antenna. (Feeders are three wavelengths each.) A small building 140 m from the antenna tower houses the power, control and data acquisition/storage equipment for the receiver. The receiving antennas for 35 through 104 MHz are five element crossed Yagi pairs modified to optimize intrapair isolation. The antenna for 147 MHz is a fourteen element crossed Yagi pair. All antennas are mounted approximately 1.5 wavelengths above ground as mentioned earlier. The main features of the terrain are the Great Land Glacier, the P-Mountain Range 10-20 km southeast of the receiving site and the almost flat near foreground. The glacier and the mountain range limit the elevation angle to values greater than 1.1 to 1.7 degrees over the azimuthal extent of the antenna beam. The near foreground is very smooth, with surface deviations of only about 0.5 to 2 meters. Thus, a perfect flat ground profile is chosen to calculate the effective radiation pattern. The foreground surface is composed of gravel and stones with very little biological material, except for an occasional flower. The permittivity and conductivity of the ground are very low, similar to the condition at the transmitter site. A relative permittivity of 2.5 and a conductivity of 0.0001 S/m have been chosen for calculations of the antenna radiation patterns.

3.1.2 Sondrestrom-Narsarsuaq Link

The transmitting antennas, one horizontally polarized Yagi for each of the four operational frequencies (45, 65, 85, and 104 MHz) and additional vertical monopoles for two frequencies (65 and 104 MHz), are mounted on a wooden pole tower structure at a height of approximately one wavelength. The 45 MHz Yagi has four-element while the other Yagis are five-element antennas. The monopoles include 45 degree sloping ground-planes.

As with the transmitting antennas for the 1200 km link to Thule, the radiation pattern for the transmitting antennas to Narsarsuaq are determined by the directional properties of the antennas and by the influence of the foreground terrain. Assuming a flat foreground, it can be shown that the antennas for a 700 km link should be placed approximately one wavelength above the ground to obtain the best coverage of the common volume. Further, for a perfectly reflecting foreground this would produce a desirable 6 dB enhancement of the EIRP at an elevation angle of approximately 15 degrees.

The foreground consists of gently upward sloping terrain with the exception of a 330 m hill about 2 km off to the left of the antenna boresight. The upward sloping terrain and the hill restricts the possible elevation angle from 0.9 to 6.0 degrees over the azimuthal extent of the antenna beam. Again, the relatively smooth terrain does not seriously affect the 6 dB enhancement of the EIRP at about 15 degree elevation.

The receiving site is situated on a flat seashore near the Narsarsuaq Airport. The receiver, is housed in a shielded, thermostat controlled, box mounted on a telephone pole structure. A small building 70 m from the antenna tower houses the power, control and data acquisition/storage equipment for the receiver. The receiving antennas for 45 through 104 MHz are five element crossed Yagi pairs modified to optimize intrapair isolation. All antennas are mounted with a elevation of about 23 degrees and approximately one wavelength above ground as mentioned earlier. The main features of the terrain are the various mountain ranges surrounding the receiving site and the almost flat near foreground. The mountain range limits the elevation angle to values greater than 2.3 to 7.3 degrees over the azimuthal extent of the antenna beam. The near foreground is very smooth and is covered with thin grass in the summer and snow in winter. A relative permittivity of 2.5 and a conductivity of 0.005 S/m have been chosen for calculation of the antenna radiation patterns.

3.2 Greenland High Latitude Meteor Scatter Test Bed Data Analysis

3.2.1 Propagation Classification

The meteor classification routine operates on data sequences in which the trail classifier has identified one or more meteor trails. The routine considers three general categories of trails underdense, overdense and short duration unknown propagation. Underdense trails closely satisfy the classic equation of Eshleman or are short duration trails due most likely to head echoes or trails which are short relative to the length of the first Fresnel zone. Overdense trails have longer rise time to maximum signal and do not satisfy the underdense model. Unknown propagation are events which tend to fade very rapidly, have no definite rise or shape and are most likely due to irregularities in the E-region.

The first step in the trail classification procedure is to find all potential "events" in a sequence of records. An event begins when the lock flag is first detected and the signal to noise ratio exceeds 9 dB and ends when these conditions are no longer satisfied. Three point moving average filtering (five point at 35 MHz) is used to smooth the data. For each event, a table entry is created listing the start and end of the event (both the point and the record number relative to the start), the signal maximum, the time of the maximum relative to the beginning of the event, and the number of points for which the signal level exceeds a basic threshold of -130 dBm or 14 dB SNR which ever is greater. Events can begin and end during the same record or they may continue for many records. If no events are identified in a record, the record is marked for discard and further processing of that record ends. Records marked for discard are ignored by subsequent processing and analysis routines.

The next step in the processing is to merge fades into one large trail. A fade is defined as the time between the end and beginning of consecutive trail events. Fades less than 350 ms in duration are merged using a recursive routine. If at the end of fade-merging more than four events remain which have their start in a single record, some must be eliminated because there is header space in a single record for only four trails. The maximum of four trails was based on an analysis in the early data base software development that the probability of more than four events in a five second data record is less than 0.005. To reduce the number of trails to the maximum, the four events with the greatest maximum signal are marked for further processing. All remaining events are eliminated by marking them as non-events.

Trails with duty cycle above -130 dBm or 14 dB SNR less than 30% and trails longer than 5 seconds with less than 45% duty cycle are marked as unknown propagation mechanism. Trails longer than 5 seconds with duty cycle above -130 dBm greater than 45%

are automatically classified overdense. If there are more than 5 fades per second for trails greater than 0.5 seconds the trail is classified unknown.

Next, a minimum-mean-square-error (MMSE) exponential curve fit is applied to each remaining event. The beginning and end of the curve fit region are the maximum and end of the event respectively. Only points for which the signal+noise/noise is greater than 11 dB are considered. If there are not 5 points satisfying this criteria then a "goodness of fit measure" is not computed. The measure is the average error between the fit and the data. The time constant of the exponential fit is computed and if there is a good fit to the data, the time constant of the trail is stored for future use. If there are not enough points for the MMSE fit, an alternative time constant is computed from the slope of the first and last points satisfying the SNR requirement.

Trails for which a MMSE fit could not be made but which have a rise time greater than 0.25 of the total duration and a total duration in excess of 350 ms are overdense. Trails with a rise time (from beginning of trail to maximum) in excess of 700 ms are overdense. Overdense trails are characterized by an initial rapid rise time as the trail forms followed by continuous rise to the maximum as the trail expands. Underdense trails are characterized by an initial fast rise to the maximum.

If the time constant calculated in the MMSE fit is positive or zero the trail is considered overdense. Underdense trails must have a negative time constant indicating a decay.

Short duration underdense trails are characterized by total duration less than 350 ms regardless of whether a MMSE fit could or could not be made.

Classic underdense trails are characterized by "fast" rise time (less than 0.25 of the total duration, and less than 700 ms) and exponential decay. The average error between the exponential fit and trail is computed. If the average error is less than 3.5 dB a "good fit" to an exponential is declared. If either of these criteria (rise time or exponential fit) are not satisfied, the trail is overdense. This implies that trails with characteristics of underdense and overdense trails will generally be considered overdense.

Following classification of the type of each trail, the time of the beginning relative to the record and the underdense time constant, if applicable, are loaded into the header for the data record.

The primary limitation of the classification software is the inability of the program to resolve meteor trails which lie within sporadic-E events. A record can either be sporadic-E or meteor trail but not both. Often low level sporadic-E masks out the entire data period at the lowest frequency of 35 MHz. The auto classifier is significantly more accurate at the higher frequencies, where other scatter modes are absent. Limitations in accurate discrimination between under- and overdense signatures are a consequence of the highly complex waveforms created by multipath fading in the presence of long trails, multiple trail bursts or scatter.

3.2.2 Statistical Analysis

3.2.2.1 Fading statistics

In the two high resolution data sets from 1989, the trends were for the most part consistent with the previous lower resolution experiment. The primary difference observed was in the percentage of trails classified as underdense and overdense. Data from the fast fade experiment tended to show more underdense trails as opposed to the slow fade data.

In terms of percentages of trails showing fading, the results were very consistent between the two different data sets. As expected due to the lower noise margin and the ability to resolve the fine structure of the trails, the percent of trails showing fading was slightly higher for the higher resolution experiment. At trail durations less than 200 ms, the conclusion from the first experiment that the effect of fading is minimal was confirmed.

Consider 100 ms trails at 45 MHz with 6 dB fade depths. For the most part the percentage of underdense trails in which fading was observed was on the order of 1 percent for both the high and low resolution experiments. For the entire trail set between 1 and 4 percent of the trails at 45 MHz showed 6 dB or greater fades.

At 200 ms duration the results were similarly consistent. Approximately 2 percent of the underdense trails exhibited fading and approximately 8 percent of all trails showed fading.

In the analysis of the data several definite trends emerge. Underdense trails tend to show less fading than overdense trails. This was consistent between the two experiments. As the trail duration increases, the probability of fading increases. As expected, as the trail duration increases, the percentage of underdense trails decreases. As signal level increases, the percentage of underdense trails decreases so the percent of trails with fading will increase. As expected from the analysis of Manning, wind induced effects become apparent at about 400 ms trail duration at which the percentage and depth of fades increases. For long duration trails (defined as those exceeding approximately 250 ms), model predictions must be made more pessimistic to take into account the effects of fading.

Analysis showed that approximately 50% of the fade durations were less than 20 ms. Given the distribution of fades, techniques such as interleaving combined with forward error correction coding can be very effective in combating the effect of the fades.

3.2.2.2 Frequency diversity statistics

Frequency diversity effects were evaluated for frequency separations between 0.3 and 4 MHz at the two different paths of 1200 and 700 km. The morphology of the results are described, but little effort had been devoted to possible explanations of some rather unexpected relationships during this contract.

For example it was found that the average channel availability for meteor trail signals as described by the duty cycle of the channel was dominated by the high frequency in all but one configuration of frequency separation when the received power level exceeded approximatley -125 dBm. The opposite was the case for the sporadic E layer signals. The frequency diversity improvements are seemingly independent of frequency and range from approximately 5% to 20%. This gave rise to the expectation that the low frequency meteor signals fade more often than the high frequency signals.

However, the distribution of durations presented subsequent to the duty cycle statistics show that the durations of the low frequency in more than half of the configurations of frequency separation and power level are longer than the durations of the high frequency signals. Thus there is not a clear indication that the high frequency signals fade less than the low frequency signals. Likewise, it is not clear that the durations of the low frequency sporadic E layer signals are consistently longer than the duration of the high frequency signals, although the statistics support that this is almost the case.

The immediate impression when viewing a large number of meteor trail signals is that the frequency diversity effects occur during formation of the trails, i.e. the first 50 msecs at low signal levels, and especially during the final decay of long enduring signals. However, the statistics describing the diversity improvement as a function of the time since the formation of trails show this not to be the case for the total population of trail signals.

The major improvements are found within the first few hundred milliseconds after the formation of the trails. This most probably reflects the fact that the endurance of the majority of the signals is less than 500 msec, and the rather spectacular examples of large differences between high and low frequency signals found in the data sample for long enduring signals are not descriptive of the full sample.

In conclusion, dual, close spaced frequency diversity seems to offer a limited improvement of the channel properties to the communicator, and no frequency separation dependence of the diversity improvement was found. However, the apparent lack of a monotonic frequency spacing dependence of the diversity improvement leaves questions as to the physical causes of the variability of the signal endurance and the fading mechanisms. It is speculated that day-to-day changes in the neutral atmospheric density, the high altitude winds and the sporadic E layer ionization should be investigated as candidate mechanisms.

3.2.2.3 Antenna polarization statistics

A survey of the depolarization mechanisms present in meteor scatter propagation during undisturbed ionospheric conditions as well as at different levels of absorption during a PCA had been conducted. The sources of depolarization on the total propagation path for a meteor scatter link have been identified.

Preliminary results of the computation of the ionospheric depolarization have be presented. The results show that Faraday rotation can create significant polarization mismatches during undisturbed ionospheric conditions if the meteor trail occurs at altitudes above 100 km and the frequency is 45 MHz or below. The bulk of the meteor trails are found below 100 km, and it is anticipated Faraday rotation will not create much degradation to the efficiency of the meteor scatter link. However, during PCA's ionospheric depolarization is present at lower altitudes and may contribute considerably to the effective pathloss for the link.

3.2.2.4 Waiting time statistics

3.2.2.4.1 Diurnal variations of waiting times

The waiting time is as expected frequency dependent. The waiting times are much lower at 45 MHz than at 65 MHz and the waiting time at 104 MHz is the longest in all cases. The waiting time also increases with a decrease in transmitter power. In some cases, the waiting time is undetermined or exceeds 10,000 seconds which is the realistic limit for the statistics to be valid. Thus, some time blocks, especially with transmitter powers less than 100 W, do not have a waiting time associated with them, as not enough trails were available to support the propagation.

At 45 MHz, however, another reason for missing data points exists. In June, between 10 UT and 20 UT data points are missing even at transmitter powers of 1 kW and 10 kW, while at the same time the waiting time is low, in the order of few seconds, on the edges of this time interval. This is caused by sporadic E-layer propagation supplying a near continuous propagation path between 10 UT and 20 UT. This means that there was no waiting time, but also that the meteor signals were obscured and the waiting time due to meteor trail signals could not be derived from the test-bed data.

At 65 and 104 MHz the meteor trail signals provided enough connnectivity to enable the waiting time to be derived.

The diurnal variation is a function of season. In February a variation of approximately a factor 3 is seen. A shallow minimum in the waiting time occurs at about 0600 UT and the maximum around 1200 UT coinciding with the diurnal galactic noise maximum for the month of February. A secondary minimum is found around 1600 UT which is most likely caused by the presence of the diurnal galactic noise minimum at this time during the month of February, combined with meteor trails arriving over the north pole. This contribution of meteor trails from the morning side of the earth is presumed to account for the partial absence of a late afternoon arrival rate minimum at high latitudes. For calculating local time, the midpoint of the link is geographically four hours west of Greenwich.

The diurnal variation is less pronounced in March where the diurnal noise maximum occurs at 10 UT coinciding with the early morning maximum of meteor influx. The effects of higher noise and larger arrival rate of meteor trails counteract each other and the diurnal variation of the waiting time is smoothed out as a result. The overall waiting times are shortest in June compared to the other months, but a larger diurnal variation is seen as the increase in waiting time caused by low arrival rates around midnight UT is enhanced by the presence of the diurnal noise maximum at the same time.

The magnitude of the diurnal variation seems to increase with frequency for transmitter powers less than 100 W. This is most likely an artifact of the statistics, as only few meteor trail signals have been available for computation of waiting times in excess of 30 minutes. Longer waiting times, presumably of limited interest, must be used with caution.

3.2.2.4.2 Waiting time as a function of transmitter power

As with the arrival rate statistics, we would expect the waiting time vs. transmitter power statistics to show a change of slope as the waiting time moves from being dominated by underdense trails at high power. For the power levels modeled by the data base there appears to be no abrupt knee or change in slope but a slow change indicating a very gradual shift in the contribution from overdense to underdense trails.

The waiting time at 45 MHz approximately doubles each time the duration is doubled over the range from 50 to 400 msec. At 65 and 104 MHz the waiting time increases by a factor of about 2.3 and 2.6 respectively each time the required duration is doubled.

The seasonal variation shows minimum waiting times in June, very little difference between the waiting times in February and March, and surprisingly little difference between waiting times in September and December. The December waiting times could have been expected to be longer than the September waiting times as the meteor trail arrival rate is larger in September than in December. In September, the percentage of long durations, especially at high values of SNR was much less than during the other months. Thus, shorter durations, not lower arrival rates must be the cause for the longer than expected waiting times in September.

3.2.2.4.3 Waiting time as a function of duration

Waiting times have also been computed as a function of duration for the selected transmitter power levels. As expected, the waiting time significantly increases with frequency. It takes six times longer to deliver a message requiring a 200 msec signal at 65 MHz than at 45 MHz and about 20 times longer at 104 MHz. Also, 100 W transmitter power is seen to be the practical lower limit for 45 and 65 MHz, whereas 1 kW is needed at 104 MHz to obtain waiting times less than several thousand seconds. Again, the seasonal variation shows little difference between February and March and the shortest waiting times are found in June. The waiting times in September differ very little from the waiting times in December.

3.2.2.4.4 Waiting time as a function of frequency

Finally, the averag^ waiting time statistics are presented as a function of frequency and duration for four selected power levels (10 W, 100 W, 1 kW, 10 kW). It can be seen that for meteor signal durations from 50 to 400 msec, and regardless of frequency (45, 65 or 104 MHz), the waiting time can be reduced by a factor of about three and one-half by increasing the power from 100 W to 1 kW. For meteor signal durations of 200 msec at 65 MHz, the waiting time can be reduced by about a factor of six if the power is increased from 100 W to 10 kW.

The waiting times are dominated by underdense trails as expected, except at transmitter power levels of 10 W and 100 W where they are dominated by overdense trails. At a first glance it may seem paradoxical that the waiting times can be dominated by overdense trails, but by comparison with the arrival rates presented in Appendix B, it can be seen that at low power the low frequency, short waiting times are indeed dominated by overdense trails.

3.2.2.5 Polar cap absorption event statistics

Data acquired with the 1200 km GL High Latitude Meteor Scatter Test Bed between Sondrestorm AB and Thule AB in Greenland during solar disturbances in March and August of 1989 has been analyzed and presented. The solar disturbance of August 1989 resulted in a Polar Cap Absorption event reaching 12 dB zenith absorption at 30 MHz. The test bed, operated at 35, 45, 65, 85, 104 and 147 MHz, was significantly influenced by the absorption. All frequencies lower than 104 MHz were interrupted for periods ranging from a few hours to one day during the part of the event where the zenith absorption exceeded 10 dB. No interruptions occurred at 104 MHz although a slight decrease of duty cycle was noted. The absorption was highly frequency dependent. Operation at frequencies in the range 65 to 104 MHz outperformed 35 and 45 MHz during the most severe absorption. The solar disturbances in March 1989 produced a weak PCA with a maximum zenith absorption of 3 dB. Little effect was seen from the absorption, but very strong solar noise bursts decreased the signal-to-noise ratio on all frequencies and caused interruptions. It is speculated that solar noise bursts present during previous Solar Proton Events could have been the basis for expectations that the absorption at VHF frequencies during these events was frequency independent.

3.3 Instrumentation for the Analysis of Artificial Ionospheric Disturbances

The capabilities required for the Arctic PCA experiment and the VOA ionospheric heating experiments are both satisfied by the multiple antenna system configuration and the coherent integration and Doppler analysis of the HF Channel Probe. The amplitude and Doppler accuracy has been tested and found acceptable while the phase measurement has been observed but not yet calibrated and verified. An on-the-air verification of the angle of arrival measurement accuracy and performance in terms of signal-to-noise ratio (i.e. verification of the expected signal processing gain) will be conducted at the University of Lowell's Millstone Hill field site. Also to complete this verification further analysis of the characteristics of the RACAL 6790 receiver in the presence of strong signals will be conducted using an HF spectrum analyzer. The dynamic range of the RACAL 6790, approximately 90 dB and more if the correct frequency separation is used, is very impressive but the experimental requirement for 90-100 dB of out-of-band signal rejection indicates that further precautions would be prudent.

4.0 PRESENTATIONS AND PUBLICATIONS

4.1 Presentations

J. Ostergaard, "Investigation of meteor scatter propagation between Thule and station Nord," presented at the annual meeting of the Commission for Scientific Research in Greenland, Copenhagen, Denmark, April 1990.

4.2 Publications

J. C. Ostergaard, J. A. Weitzen, P. A. Kossey, A. D. Bailey, P. M. Bench, S. W. Li, J. R. Katan, A. J. Coriaty and J. E. Rasmussen, "Effects of absorption on high latitude meteor scatter communication system," Proceedings of the Ionospherics Effects Symposium, Springfield, VA, May 1990.

J. C. Ostergaard, J. A. Weitzen, P. A. Kossey, A. D. Bailey, P. M. Bench, S. W. Li, J. R. Katan, A. J. Coriaty and J. E. Rasmussen, "Effects of absorption on high latitude meteor scatter communication systems, 1990 IEEE MILCOM Conference Proceedings, Monterey, CA, October 1990.

J. C. Ostergaard, "Experimental Determination of Waiting Times for Meteor Trail Returns of Specified Duration, February, March, June, September, December 1989," prepared for BSD/MGEC, 19 March 1990.

J. C. Ostergaard, "Criteria for the Classification of Overdense and Underdense Meteor Scatter Ratio Returns from the USAF/GL High Latitude Meteor Scatter Test Bed," prepared for BMO/MGEC, 23 March 1990.

J. C. Ostergaard, "Antenna Pattern Description. Geophysics Laboratory High Latitude Meteor Scatter Test Bed," prepared for BSD/MGEC, 26 March 1990.

J. C. Ostergaard, "A Statistical Characterization of Fading on Meteor Communication Channels," prepared for BSD/MGEC, 10 May 1990.

J. C. Ostergaard, "A High Resolution Statistical Characterization of Fading on Meteor Communication Channels," prepared for BMO/MGEC, 28 September 1990.

J. C. Ostergaard, "Investigation of Frequency Diversity Effects on Meteor Scatter Links in Greenland," prepared for BMO/MGEC, 30 September 1990.

J. Ostergaard, "Preliminary Investigation of Faraday Rotation Effects and Description of Polarization Measurements on the AFGL High Latitude Meteor Scatter Test Bed," 1 January 1989.

J. Ostergaard, "Meteor Scatter Communication Between Thule and Station Nord. A Feasibility Study," February 1990.

4.3 Scientific Reports

Jay A. Weitzen, "USAF/GL Meteor Scatter Data Analysis Program. A Users Guide," GL-TR-89-0154, Scientific Report No. 2, June 1989, ADA214988.

J. Ostergaard, "Meteor Scatter Communication Between Thule and Station Nord, Greenland," GL-TR-90-0248, Scientific Report No. 3, September 1990, ADA234440.

J. A. Weitzen, J. C. Ostergaard and S. W. Li, "A High Resolution Statistical Characterization of Fading on Meteor Communication Channels," GL-TR-90-0329, Scientific Report No. 4, November 1990, ADA235548.

J. A. Weitzen and J. Ostergaard, "Statistical Characterization of Fading on Meteor Scatter Communication Channels," GL-TR-90-0362, Scientific Report No. 5, December 1990., ADA235148