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CHARACTERIZATION OF PROPAGATION AND COMMUNICATION PROPERTIES OF THE NATURAL AND ARTIFICIALLY DISTURBED IONOSPHERE

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This basic research project, conducted during the period starting 12 September 1990 and ending 12 December 1994, studied the effects of natural and artificial ionospheric disturbances on HF and VHF propagation and communication. This project was reasonably divided into two parts where each stood by itself; VHF meteor scatter investigation and HF ionospheric modification studies. In addition to these two studies, a third study was later added to the project to include a Joint Electromagnetic Warfare Center (JEWC) electromagnetic wave propagation and signal loss study. Each of these studies are addressed independently within this final report.

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1. INTRODUCTION

This basic research project, conducted during the period starting 12 September 1990 and ending 12 December 1994, studied the effects of natural and artificial ionospheric disturbances on HF and VHF propagation and communication. This project was reasonably divided into two parts where each stood by itself; VHF meteor scatter investigations and HF ionospheric modification studies. In addition to these two studies, a third study was later added to the project to include a Joint Electromagnetic Warfare Center (JEWC) electromagnetic wave propagation and signal loss study. Each of these studies are addressed independently within this final report.

1.1 VHF Meteor Scatter Investigations

This research project represents new efforts that follow-up earlier research on the properties of the meteor scatter channel at high latitudes. It is aimed at characterizing the propagation and communication properties of meteor scatter during both quiet and disturbed ionospheric conditions. The primary facility used for this research is the Phillips Laboratory High Latitude Meteor Scatter Test Bed in Greenland. The test bed consists of two diagnostic meteor scatter links, one 1200 km between Sondrestrom AB and Thule AB, one 700 km between Sondrestrom AB and Narssarssuaq in Greenland. The links operate throughout the frequency range 35 MHz to 147 MHz covering the frequencies of interest for meteor scatter propagation. The 1200 km link is situated entirely within the Polar Cap Area and is intended for the study of the seasonal and diurnal variation of meteor trail availability as well as the effects of Solar Proton Events (SPE) and their associated Polar Cap Absorption's (PCA) on meteor scatter. The 700 km link passes through the auroral oval and is intended for studying the effects of auroral absorption and scattering on meteor propagation. In addition the link provides data for studying the influence of the path length on the availability of meteor trails during quiet ionospheric conditions.

A full year's collection of data on both links has been completed, and routine operation has commenced on the Sondrestrom - Thule link. The data on the Sondrestrom - Narssarssuaq link had been previously collected under Air Force contract F19628-88-K-0004 Thus large amounts of data have been collected and made available for statistical analysis of the propagation and communication properties of the meteor scatter channel. The software used to classify meteor scatter signals and process the raw data into suitable data bases have been significantly upgraded to efficiently process the large amounts of data collected.

1.2 HF Modification Study

This basic research project represents a follow-on to an earlier effort to investigate the effects of high power HF transmitters on the ionosphere at distances of 400 to 1200 km from the transmitter. These earlier experiments were carried out in the southern US from Delano, CA to Shreveport, LA, a distance of 2400 km. The actual heated area was some 1200 km from Delano over the Albuquerque region. Standard techniques were used to sense the changes produced by the Delano system which at that time operated with an effective radiated power (ERP) of about 83 dBW. The actually achieved power varied depending on the chosen frequency, affecting both the SWR achieved and the antenna gain which varied across the frequency band, increasing by about 6 dB from the low end to the high end of each band.

Under this project a repeat of the January 1990 measurements were conducted using the higher power levels of the Voice of America (VOA) having completed the changes to their Delano system to combine three transmitters on their new 2-D antenna, thereby increasing the power level by about 5 dB.

1.3 JEWC Study

The objective of this study was to continue development for a Joint Electromagnetic Warfare Center (JEWC) capability to simulate electromagnetic wave propagation and signal loss in a wide variety of propagation media and terrain features that encompass a complete range of anomalous propagation conditions, topographical irregularities and surface moisture and cover. The study was to examine, modify and develop, as needed, the improved and additional computer programs to handle the propagation regimes applicable to the operational environment of interest. In addition, this study was to examine and identify the code capabilities and limitations together with the means to control computational error and ways to benchmark the quality of the code output.

2. SCOPE OF WORK

Each of the three elements encompassed under this contract can be independently addressed. This section details the comprehensive efforts accomplished under each of these three areas during the conduct of the contract.

2.1 VHF Meteor Scatter Investigation

Efforts accomplished under the VHF meteor scatter investigations were aimed at characterizing the propagation and communication properties of meteor scatter during both quiet and disturbed ionospheric conditions using the Phillips Laboratory High Latitude Meteor Scatter Test Bed in Greenland. During the conduct of the contract, additional test beds were developed in Brazil and CONUS. A summation of the efforts accomplished are provided in the following paragraphs.

2.1.1 Phillips Laboratory High Latitude Meteor Scatter Test Bed in Greenland

The High Latitude Meteor Scatter Test Bed was comprised of two diagnostic links: Sondrestrom AB - Thule AB (1200km link) and Sondrestrom AB - Narssarssuaq (700km link). Efforts associated with each link are further defined in the following paragraphs.

2.1.1.1 Sondrestrom - Thule Link

At the start of the contract, October 1990, a visit to Thule AB by UMLCAR engineering personnel accompanied by Phillips Laboratory personnel, was conducted for the purpose of performing a general revision of the receiving equipment and removal of excess equipment for return to Hanscom AFB. The receiving station was calibrated and the effective noise temperatures of the receiving system were determined. The propagation environment monitor consisting of two riometers and a tri-axis magnetometer were serviced. Software upgrades were installed and the riometers were calibrated and the magnetometer sensor leveled since the concrete pad that the sensor is standing on is installed in permafrost requiring a yearly leveling to compensate for frost heaving during the summer. Repairs were performed on the VLF/LF ionosounder transmitter due to a faulty trigger thyratron requiring replacement. General training with maintenance personnel was conducted.

A high gain yagi antenna for 104 MHz was designed for an experiment on the Sondrestrom Thule meteor scatter test bed. It was found during the polar cap absorption events of 1989, that 104 MHz persisted through a large scale event, but that the communication capacity was inherently low due to the high frequency. The inherent capacity can be improved with high gain antennas, and it was decided to field such antennas at both ends of the link and collect propagation data during the time slot previously used for 147 MHz. Commercially built antennas were not readily available, so a design of a 12 element antenna based on components from Scala, Inc. was undertaken. The basic antenna was then used to form quad arrays of horizontally polarized antennas for transmitting and cross polarized antennas for receiving. Special software was written for analysis of these arrays vs. element spacing and distance above ground. The antennas were manufactured by Scala and were deployed in March 1991 before the PCA season began. The deployment in Thule went as scheduled, whereas terrain features in Sondrestrom necessitated further computations before a final position could be chosen. The first results using the high gain antennas indicates that the antennas increase the meteoric arrival rate and signal levels by a large amount. The exact magnitudes are still not available, pending reception and analysis of some months of data. A very large PCA occurred in late March. The computed vertical absorption was 38 dB. This magnitude is large enough to exceed the survivability threshold for even the new high gain array system at 104 MHz.

During the March campaign it was discovered that the UPS supporting the Thule receiver was malfunctioning due to dead batteries. This brings to attention an improved maintenance procedure to secure that the batteries are still functioning, and also emphasizes the inherent limitations of lead acid batteries. A real good UPS should have NICAD batteries, and preferably the computer system should not need a UPS, if procedures to perform a graceful shutdown can be implemented.

During May 1990 a field campaign was conducted to perform in-situ evaluation of field analysis software and to assist the Navy in performing a wide range of special investigations in meteor scatter and HF packet communications. A major software development had been undertaken to produce acquisition and processing software for both meteor scatter links. Previously, processing bottlenecks had delayed the production of data bulletins, and the new software was aimed at doing as much processing as possible in conjunction with the data acquisition. Thus acquisition, classification and processing of the acquired waveforms into daily databases of arrival rate duty cycle and duration now takes place in the field at each station. The raw data, log files, classification information and databases are stored on optical disks each holding one months data for a particular station. Two operating modes are available with the software. One acquires data for 30 minutes each hour and performs processing for the remaining 30 minutes. This software operates on a standard Z-248 computer. The other mode utilizes a VM386 operating system capable of running two virtual DOS machines on a single 386 computer. One machine continuously acquires data, while the other processes data already acquired. This way data can be continuous collected on the links.

During October 1992 new antennas and a new temperature stabilized enclosure for the riometers were installed. The antennas are 10 element circular polarized (crossed 5 elements) Yagis. While at the station, the annual leveling of the magnetometer sensors took place. Calibration information, antenna patterns and new quiet day curves were derived and forwarded to the station and to NOAA/SES. The quiet day curves are now stable, and computations have been performed to model the radiation patterns of the new antennas. Thus, quiet day curves and antenna correction patterns have been determined. The computed and measured quiet day curves agree except for a contribution from low angle sidelobes present in the computations. The reason for this discrepancy is still under investigation.

During the second quarter of 1993 detailed analysis of the influence of ionospheric absorption on meteor scatter links based on data from the Sondrestrom - Thule link was started. Such analysis was one of the two main efforts anticipated when the Greenland testbed was constructed, the other being the seasonal and diurnal variation of meteor trail availability at high latitudes. The analysis attempted to determine the frequency dependence of the ionospheric absorption during solar proton events (SPE). The first effort was centered on the construction of a computation model of absorption based on particle fluxes measured by the GOES-7 satellite. The model is capable of predicting the absorption measured with the Thule riometer accurately when the absorption is in the 2 to 15 dB range. At lower absorption levels the model predicts less absorption than measured. Simultaneously, antenna noise power and meteor trail arrival rates measured with the Sondrestrom - Thule meteor scatter link during a number of large SPE events in 1989 were under examination. The results of this examination will be used to evaluate the suitability of the model for forecast purposes. A report of these findings were presented to PL during the fourth quarter of 1993 under a PL cover.

Also during the initial quarters of 1993, the transmitter of the Sondrestrom - Thule link failed. Repair of the transmitter was delayed pending a decision on the long term requirements for the link. During the fourth quarter of 1993, the Air Force decided to discontinue the meteor scatter program and subsequently, the diagnostic equipment in Sondrestrom and Thule was dismantled and returned to Phillips Laboratory.

2.1.1.2 Sondrestrom - Narssarssuaq Link

During the first quarter of the contract, a special investigation was performed using the Sondrestrom - Narssarssuaq link to provide support to the US Navy on simultaneous meteor scatter and HF availability for a short path through the auroral zone. In conjunction with this campaign, the meteor scatter test bed link between Sondrestrom and Narssarssuaq was calibrated and then dismantled. The equipment was returned to Phillips Laboratory.

2.1.2 Phillips Laboratory Meteor Scatter Test Bed in Brazil

At the start of the contract, a single frequency, 1 kW transmitter with an output level control was assembled from a Henry power amplifier and a crystal oscillator-driver developed specially for this purpose, including a laboratory timer. The transmitter was extensively tested in the laboratory. One existing meteor scatter receiver was modified to operate in a warm climate rather than in the Arctic, by improving the heat transfer through the receiver box. This receiver was used for the initial data collection in Brazil. It was later replaced with one of the new series of receivers.

In August 1991, the meteor scatter link in Brazil was installed between San Jose Dos Campos and Santa Maria in Southern Brazil. The first tests proved the link to be working, but receiver damage incurred during installation made necessary some repairs of the signal lock flag. The following quarter, the receiver lock flag problem was solved and the cooling plate was mounted. This solved the temperature overrun and the link was operating as anticipated. Data is being generated and analysis efforts are ongoing.

A major software development was undertaken to produce acquisition and processing software for the Brazil link. Previously, processing bottlenecks have delayed the production of data bulletins, and the new software was aimed at doing as much processing as possible in conjunction with the data acquisition. Acquisition, classification and processing of the acquired waveforms into daily databases of arrival rate duty cycle and duration takes place in the field at the receiving station in Brazil. The raw data, log files, classification information and databases are being stored on optical disks each holding one months data for the station.

A software package to derive communications related statistics such as throughput for fixed speed and ideally adaptive signaling schemes, as well as message waiting times for fixed speed signaling schemes was developed. This package was not as extensive as the one available for the Greenland data, but provided standard communication statistics to illustrate the potential of the Brazil link.

During November 1991, a first look at data from the Brazil link revealed that the propagation conditions were not quite as simple as anticipated. The link is dominated by what is believed to be Equatorial spread-F propagation and sporadic-E propagation for many hours each day. Meteor scatter signals are also found, but it still remains to be seen if reasonable statistics for meteor scatter propagation can be computed from the data. As a result, an examination of the first Brazil data illuminated some problems with the PC version of the auto-classifier program. They were fixed, however, it was noted that the classifier cannot be expected to perform very well in an environment where more than 50% of the signals are non-meteoric.

The diagnostic meteor scatter link operated by PL and CTA of the Brazilian Air Force was visited in May, 1992. New receiver software was installed, and the original receiver destroyed by lightning was replaced. A transmitter repair was attempted, following the breakdown of a transistor driver stage, but spare parts not available in Brazil were needed.

At the request of the Brazilian Air Force, refurbishment of the diagnostic meteor scatter link between San Jose Dos Campos and Santa Maria in Brazil including the repair of two receivers, a transmitter driver amplifier, and resurrection of the data acquisition and analysis software were scheduled for the fourth quarter of 1993 as well as a short data acquisition campaign. The aims of the campaign were to ensure proper long term operation and to attempt identification of the long lasting scatter modes of propagation occurring around midnight and noon. However, in December 1993 personnel traveled to Brazil in an attempt to repair the Brazil link and found that damages as a result of lightning to too excessive to economically repair. At the close of the contract the Brazil link had not been repaired and many parts of the link had been returned to Phillips Laboratory as a result of the decision to cancel the meteor scatter program.

2.1.3 Phillips Laboratory Meteor Scatter Test Bed in the Continental United States (CONUS)

At the start of the contract, design and prototyping of a single frequency meteor scatter receiver for use in the CONUS link was started. Apart from the single frequency capability, the main difference between the existing receivers and the single frequency version is that the gain stabilization in the latter is obtained by temperature compensation rather than temperature stabilization. The aim of this is to obtain a receiver that can operate over a wider ambient temperature range than the existing receivers primarily intended for the Arctic. A crystal oscillator with better modulation characteristics was designed for the CONUS transmitter because the FM modulation linearity was not as good as anticipated for the crystal oscillator driver constructed for the Brazil transmitter.

It was anticipated that omnidirectional antennas for the CONUS links would be made available by other Air Force agencies. However, this was not the case and some design efforts were undertaken to suggest a suitable antenna, based on a concept of three circularly arranged dipoles fed in phase.

During the third quarter of the contract, extensive discussions and planning meetings at PL and BMO were attended during the initial stages of the planning of the CONUS link program. These meetings defined the aims and schedules of the program. The CONUS program was reduced to comprise only one 1200 km long link in a North-South direction.

By the fifth quarter, the single frequency version of the existing meteor scatter receiver had been prototyped and tested. A working prototype was available as of mid-December. Delivery of six receivers was anticipated in April 1992.

During the fifth quarter, a noise survey was performed in Montana for prospective transmitter site. The noise survey instrumentation was constructed around a Tektronix spectrum analyzer, a Disc-cone antenna with a suitable band pass filter and a pre-amplifier. Data was collected and analyzed by a PC.

During the sixth quarter, preparation of the CONUS equipment into the shelters was conducted with training sessions being held for the field crews. During the seventh quarter, preparations for installation of the diagnostic meteor scatter link between Montana and New Mexico was continued. Noise surveys were undertaken at a number of sites in Montana as well as in New Mexico. Based on the results of these surveys, a transmitter site at Glendive, MT and a receive site at Cimarron, NM were chosen. The installation of the CONUS diagnostic link was concluded during the eighth quarter. Test operation of both sites were performed. The link ran for a short period, until the transmitter failed due to a power line overload that destroyed the final amplifier tube. A new, lower power transmitter was ordered as a replacement, however, installation of the replacement transmitter would not be performed before testing at the laboratory. Subsequent to the transmitter failure, the receiving station was destroyed by a lightning stroke to the power line. Lightning and power line surge protection will be needed at both stations before further operation could be contemplated. A spare Greenland type receiver had been provided for the receiving station.

During the tenth quarter, the CONUS link was removed from the western US and efforts to place the link between NRL in Washington D.C. and Phillips Laboratory in Massachusetts were ongoing. However, during the twelfth quarter, the Air Force canceled the meteor scatter program and subsequently the CONUS link equipment was not deployed.

2.2 HF Modification

At the start of the contract, emphasis was placed on continued evaluation of data collected during a 1990 IONMOD campaign conducted under a previous Phillips Laboratory contract. Emphasis was placed on those periods when we expected the heating process to be most favorable and an investigation of the received heater signal at Barksdale as Delano cycled the high power transmitters on and off.

During the second quarter, data playback was completed for each of the nighttime experimental runs carried out during the 1990 campaign. The special heating periods, those where the heater frequency was within 1 MHz of the maximum usable frequency for the path from Delano to Barksdale were examined and no indication of the effects of the high power heat on the HF probe signal, either in the amplitude, elevation angle or on the Doppler frequency, all on the stronger "low" ray more sound. The high ray, typically, is considerably weaker and appears irregularly in the data and could not effectively serve to detect the effects of the heater on the ionosphere. This was as expected based on our ray tracing results.

During portions of the analysis there were several periods when the three heater transmitters were cycled off and on in an attempt to see whether the changes in transmitter power would correlate with changes in the probe data. During this analysis the new VOA channel data in the probe system was examined for indications of the heater power. It was found that we often had great difficulty in recognizing whether there was one, two or three high power transmitters on the air, using as a reference, the VOA computer printout log to indicate the number of transmitters "on" at any particular time.

At first we considered the possibility that the fading associated with most of the received signals from Delano were making it difficult to determine the actual amplitude of the received heater signal. We then decided to utilize a statistical approach and a scatter diagram of received probe signals versus heater signal, both received at Barksdale. These data were divided into two parts, one when one VOA transmitter was on the air and the second part was when all three transmitters were operating. This scatter plot allowed for the fading in that it was assumed that the fading was the same on both signals. The median level for the high power transmitters, one or three were the same.

After discussions with Phillips Laboratory personnel, it was concluded that very likely VOA had not properly phased the three transmitters for the particular steer angle required for Barksdale; the steering of the array towards Barksdale upset their careful phase calibration. Very likely the matched conditions on the transmission lines feeding the array was changed by the steering and the reflected wave on the line, in turn, altered the phase at the sensing point.

Whatever the exact explanation, the data clearly indicated that the three transmitters did not appear to provide a signal at Barksdale any greater than for one transmitter. This means that the achieved effective radiated power was approximately 9 dB below what was expected and what is considered likely to produce measurable heating effects. At this point the material was briefed at the Phillips Laboratory to a joint group from Phillips Laboratory, RADC and the MITRE Corporation. It was our feeling that an additional campaign would be necessary and began planning for such an event.

During the first half of the third quarter, planning and preparation for the IONMOD test to be conducted in May/June were carried out. Among the tasks completed during this time were:

- Construction of circularly polarized antennas in an attempt to decrease the short period fading that often hampered the analysis of previous tests. The two loops that made up each antenna were designed to have their circular planes perpendicular and parallel to the dip of the magnetic field at Barksdale. This together with being able to alter the preamplifiers allowed for the possibility of a highly elliptical polarized probe signal.

- The construction and testing of a new on site calibration mode for the circularly polarized antennas. The calibration antenna would be geometrically central to the three receive antennas and transmit a known signal so that each receive antenna receives the same phase and signal strength.

- The full set up and testing of the probe equipment including the testing of some updated software, performance of the new calibration system and determining the true dynamic range of the RACAL receivers.

- Testing the magnetic loop stick antenna for frequency response by using a Helmholz coil. Even though this test determined that the loop stick antenna was effective over the required frequency range, the system used for testing could not make quantitative measurements of the antennas response to particular field strengths.

Over the period 21 May 1991 to 3 June 1991 the IONMOD experiment was conducted on site at Barksdale. The initial part of the onsite work from 21 May to 24 May consisted of installing and testing all equipment including the correct positioning and orientation of the circularly polarized antennas. On the 24th and 25th of May, the system was tested using just the probe transmitter at Delano. Heating with the VOA transmitter was conducted over the period 25 May to 1 June.

After the experiment, several planning meetings were held to organize the analysis of the data. By the end of June preliminary results indicated that both amplitude data from the probe system and vertical incidence ionograms from the midpoint probably contained effects due to heating. These preliminary observations were then examined more fully.

Several different approaches were used to detect periodic variations in the received probe signal, operating at a frequency very close to the heater (VOA) frequency, that coincide with the 10 minute cycling, on and off, of the transmitter. On four different periods, typically 30 to 50 minutes in duration, on different days, it was possible to detect changes in the received probe signals that are in very close coincidence with the heater cycling, however, these changes appeared only in the amplitude of the received probe signal and indicated a strong tendency for reduced amplitude during the heater-on periods.

The comparisons were always made between a heater-on period and the adjacent heater-off periods. These changes were relatively small and the detection process was made difficult by the relatively rapid 6 to 10 dB fading on the probe signal. The documentation of these effects continued to build up a database for those times when heating was observed and those times when no effects were found. Numerical and analytic ray tracing techniques were used with the measured ionospheric profiles to determine the ray paths through the heated regions as the relationship between the heater frequency, which was essentially 12 MHz for all of the above observations, with the changing ionospheric conditions, the changing maximum frequency for the path from Delano to Barksdale (2400 km).

Analytic ray tracings were carried out using the electron density profiles measured during the experimental period near the midpath point at Kirtland AFB, NM. These ray tracings showed the location and structure of the heated region by the density of the rays near the reflection region. From this analysis the heated region can be described as consisting of two branches; one along the skip rays and the other horizontally along the reflection height.

A second set of ray tracings for the probe signal were carried out to see the path that the probe signal takes through the heated region. As the critical frequency and height of the F-layer changed during these experiments. These changes cause the geometrical relationship between the heated region and the probe path to change. As the MUF along the ray path increased, the probe signal passed through the lower portion of the skip branch of the heated region and finally, when the MUF exceeded the heating frequency by more than 3 MHz, the probe intersected the heated region below the bottom of the ionosphere. At this point, the effects of the heating should disappear. This analysis of the probe path and the heated region explained why the effects of the high power transmitter were not always seen on the probe signal.

In conjunction, calculations of the magnitude of the F-region heating at the heights associated with these experiments that were carried out in late May, 1991. For this experimental period, the height of the Fmax was around 400 km, compared to 250 km for the ionospheric models used by E. Field to analyze the earlier Soviet measurements. The increased height of the ionospheric layer for our experiments means that the heating of the local plasma is more difficult.

During the sixth quarter, Dr. Sales, UMLCAR, was invited to participate in a workshop sponsored by Phillips Laboratory (Mr. John Hecksher was the organizer) to search for potential application of the VOA high power HF facility to the problems of the AOTH technology. The results of the IONMOD experiments were presented to acquaint the participants with the capabilities of the VOA system and to convince them that the VOA system affected the ionosphere some 1200 km from the transmit site. At the meeting, discussions were held with Dr. Dennis Papadopolis, University of Maryland, on the likelihood that the observed changes in the probe signal were caused by F-region modification. He expressed his doubts about the F-region theory. Upon return to Lowell we examined the problem and quickly realized that, at the high F-region altitudes observed during IONMOD, there were insufficient collisions between electrons and neutrals to be able to significantly heat the ionosphere. Looking for a better explanation, we considered that the heating might take place in the nighttime E-region and undertook a "back of the envelope" calculation to estimate the additional absorption that might occur in the weak E-region at night.

Our analysis of the changes in temperature of the electrons in the F-region revealed that it was not possible to significantly heat the ionosphere at such high altitudes (i.e., above 300 km). After some considerable thought, it was decided that the heating must lie in the E-region around 100 km and might be associated with the presence of nighttime sporadic-E (Es) on the up-leg of the signal from the VOA high power transmitter.

Calculations showed that heating of the very weak night E-layer (foE $\approx$ 0.6 MHz) could contribute no more than about 0.5 dB additional absorption. Then attention was turned to the Es layers that were present on most nights during these summertime experiments and similar calculations showed that an additional absorption of 2 to 3 dB was possible depending on the assumed foEs and hEs. Direct measurement of the Es intensity and altitude with our vertical sounder was not possible since we were located some 700 km to the east of the one hop E-region penetration point. These calculations have increased our confidence in the Es theory of ionospheric heating.

We then expanded the work of Gurevich on the effects of wave polarization on the heating process. We included the magnetic field and of course the electron gyrofrequency. The resultant expressions reduce to the ones by Gurevich when the heater frequency >> gyrofrequency.

Work continued on the modification of sporadic-E layers by high power HF oblique transmissions. Acquired copies of papers by Koslov et al. (Geomagnetism and Aeronomy) describing their observation of a reduction in foEs during a heating experiment in the Soviet Union. This happened only once during a series of experiments when rather intense Es occurred, that is, foEs $\approx$ 8 MHz and dropped to around 4 MHz some minutes into the heating. They referenced the work of Ignat'yeva (also published in G&A). In this paper she showed that as the electrons in the Es layer heated up, the ambipolar diffusion rate increased and spread out the layer reducing the maximum electron density. We searched our data from the 1991 IONMOD experiments for such an effect. On one occasion, a strong probe signal increase occurred some three minutes into the heating cycle. A possible explanation is that as the Es layer heats up, and the Es layer becomes less dense and the probe signal is better able to penetrate the Es layer on the F-mode to Barksdale. This would explain the relatively strong increase in the probe signal strength observed on the one occasion during the May/June 1991 experiments.

Analysis then continued on the Es heating, focusing on the 7 to 10 dB signal increase observed on one occasion for three successive heating cycles. It now appeared that the transmissivity of an approximately 3 MHz Es layer was altered after about 2 minutes of heating by increased diffusion and resulted in the reduction in the electron density of the slightly denser instability patches within the Es layer. When the patch electron density is just above what is required for reflection at an oblique incidence angle a small reduction in the density results in a large increase in the signal penetrating the layer. The somewhat fortuitous configuration explains why this enhanced signal effect was seen only once. The diffusion times associated with these very thin instability patches when heated were then investigated.

During the ninth and tenth quarters, emphasis was directed to develop a comprehensive report on previous experimental efforts and analyses in a coherent and comprehensive fashion that can serve as a reference and critique on previous work including, of course, our own, on oblique HF modification. The initial phase was to have several of the important Soviet papers on this subject translated. As part of this effort, we were looking at a self consistent solution to changes in the complex refractive index, including both the electron density and the collision frequency in the E-region. Discussions with Jens Ostergaard had convinced us to try to include the velocity distribution of heated electrons in the model (Sen/Wyller theory). The report was submitted in July 1993.

During the eleventh quarter, funding for the HF Modification effort was canceled and all efforts were stopped with the exception of completing the comprehensive review.

2.3 JEWC Study

At the start of the fifth quarter a third effort was added to the contract to cover a continuation of work performed by Dr. Ronald Brent for the Joint Electromagnetic Warfare Center. This work was performed under this contract for a period of four quarters when the work was transferred to another Phillips Laboratory contract.

The primary results of the efforts by the PI, Dr. R. Brent, to date was the acquisition and study of a three dimensional geometrical optics (ray trace) numerical code called HARPO (Hamiltonian Acoustic Ray Program for the Ocean). While this is an ocean acoustic code, it was easily modified, through appropriate input parameters to be an atmospheric electromagnetic model. This is primarily due to the fact that under certain simplifying assumptions the vector EM problem is replaced by the scalar Helmholtz equation, and HARPO solves the ray equations resulting from this equation. The code to date only computed the actual rays. That is, once an environment is specified and a source is positioned with the requested bundle of ray angles, the program computes the propagation of these rays and writes them to an output file. In order to compute transmission loss at a receiver, one needs to know the exact rays (eigenrays) that pass through the receiver. Two eigenray subroutines were acquired and modified, and the PI studied them for generality and ease of use. The two routines, called EIGEN and EIGEN_RAY, use the output from HARPO to interpolate ray launch angles to yield eigenrays. Once HARPO is initially run, the output is examined and sets of rays that surround the receiver are identified. These eigenray bundles can then be recomputed. That is, the programs create output files which can then be used as input files to rerun HARPO in order to refine the results. Once there is an acceptable degree of accuracy HARPO is run requesting only the launch angles corresponding to eigenrays. This gives a plot showing all the eigenrays. The primary differences are that EIGEN is a two dimensional program, meaning that it is useful for media in which there is little azimuthal refraction, whereas, EIGEN_RAY accounts for this effect. Also EIGEN only computes eigenrays for one receiver range, while EIGEN_RAY will compute rays for several receiver ranges. This led to the belief that EIGEN_RAY will be more useful to suit the JEWC purposes. The advantage that EIGEN has over EIGEN_RAY, is that it is quicker. It is possible that both subroutines will be used with an input (or program) switch to pick a particular routine depending on the amount of horizontal refraction.

In concurrence with this issue, work on the computation of transmission loss at the receiver was performed. This is the synthesis of eigenray information and terrain information to produce received signal strength. Once all the eigenrays have been computed (for a specific receiver location) they must be "added" either coherently or incoherently to give the total field. Any eigenray that reflects off a boundary, in this case the earth terrain, will encounter some loss depending on the specific nature of the terrain. Reflection losses is a function of the angle of incidence and the local impedance of the earth. The program HARPO, was modified, at the JEWC, to handle the input of grid atmospheric refraction and terrain data. The transmission loss subroutine also had to access a terrain impedance data file in order to compute the transmission loss of a particular eigenray bundle each time it hits the earth. This loss subroutine is currently being written.

The final question that was addressed is the synthesis of all the above parts into one program. It was unsure at the time whether this is possible, since there are some decisions that will have to be made by an operator that has some knowledge of wave propagation. It was hoped that the procedure could be fully automated so that it would run from start to finish without external "human integration". The primary hope for product delivery was the prediction of total field transmission loss at a receiver, given a specified source and media. Issues of automation were not considered under this contract and were identified under the follow-on work.

The process of using ray theory or geometrical optics to predict transmission loss for wave propagation consists of three parts. The first is the calculation of rays using the program HARPO, then the calculation of eigenrays, or the rays connecting the source to the receiver, using the program EIGENRAY, and finally, the summing of all the eigenrays for the total field using the program TLOSS. During the fifth quarter, EIGENRAY was up and running and TLOSS was in its initial testing state with extensive testing to determine that its' reliability was satisfactory. The following results are presented to support these conclusions.

First, a description of the modifications to HARPO and EIGENRAY, that were necessary to access information needed to find the total field. As previously mentioned, given a source-receiver configuration, one must find all the significant rays that connect the two locations. For each ray, one must determine the ray history and print out pertinent information. For rays that have terrain or surface (for ocean problems) interaction, one must know where the interaction is in order to retract ray information. For bottom interacting rays the location is necessary for reflection coefficient data, and at all the reflections one needs to know the angle of inclination. To calculate this, flags are set in HARPO to determine whether the ray hits the terrain, and if so, the program prints out the local wave number, k, and the terrain normal, n. TLOSS then calculates the angle of incidence with a simple dot product. TLOSS also keeps a running count of all surface interactions for ocean problems and can then adjust the phase of each ray appropriately. Currently, TLOSS has a "Dummy" reflection subroutine that simply multiplies ray amplitudes by a constant factor times the number of terrain bounces, which is physically bogus, however in the following test runs cases were considered where there was no bottom interaction. This way each part of the total field calculation could be tested without too many parameters to mess analysis.

The main remaining work to be done was the implementation of caustic finding routines; first to adjust the phase of rays passing through caustics, and second to calculate the field near a caustic. For now, the information could be hard wired for certain cases of phase adjustment, and examined locations removed from caustics.

From preliminary test cases the PI was satisfied that HARPO COMPLEX was computing accurate solutions. The agreement with IFD and BELLHOP is reassuring in all cases and surprising for the lower frequency cases. The issue of proper caustic corrections is imperative, and while the automation of such corrections is difficult if not impossible in many cases, the adaptation of HARPO COMPLEX to a geometric beam program is quite possible. This will reduce operational usage from picking many parameters (or complete hand manipulation) to just choosing two. This is why it was recommended that the final operational product be a beam program built around the HARPO ray tracing program. This will be the subject of efforts in FY 1993. The PI also learned that there will be certain propagational situations where the use of a two-dimensional program will not be sufficient in determining detection. These are cases where there is extreme horizontal deflection, or cases where the source frequency is very high and subtle changes in travel time produce non-negligible phase differences. The existing codes TIREM and IREPS, while agreeing with each other, give overall levels that are much lower than HARPO COMPLEX and IFD, and this could be why there was disagreement with measured data. The disagreement of these two programs with IFD (or HARPO COMPLEX) is not surprising since they are not solving the wave equation. The reliability of VVTRPE is in question since it seemingly does not converge, even for simple problems, when the source is modeled as omnidirectional. Whether or not HARPO results will have to be calibrated to include possible absorption effects remains to be seen by comparison with reliable measured data.

The one year effort terminated at the close of the eighth quarter. The main result of the FY 92's work was the deliverable HARPO COMPLEX, which is a fully three-dimensional ray-trace program to determine the propagation of an electromagnetic (EM) signals at frequencies of roughly 10 MHz or greater. The program is able to handle continuous model terrain and refraction profiles. The incorporation of interpolated grid data for the terrain and refraction profiles was also achieved by the JEWC and could shortly be linked with University of Massachusetts Lowell program results to yield the desired final product. Testing of the current model had been carried out and good agreement with accepted numerical programs solving similar problems had been obtained. Comparisons with existing JEWC codes had also been done verifying their inadequacies causing disagreement with measured data. Full details of the JEWC work had been documented in the Final Report written for submission to JEWC by the PI.

3.0 PRESENTATIONS AND PUBLICATIONS

3.1 Presentations

J. C. Ostergaard, "Polar Cap Absorption Effects on High Latitude Meteor Scatter Link", presented at the First Annual Workshop on High Latitude Propagation Modeling, Monterey, CA, February 1991.

J. C. Ostergaard, "Effects of Frequency Diversity on Meteor Scatter Links", presented at the 1991 IEEE MILCOM Conference, McLean, VA, November 1991.

G. S. Sales, "Evidence of Ionospheric Changes Caused by a Powerful OTH HF Transmitter:, presented at the OTH Radar Technology Conference, Hanscom AFB. MA, November 1991.

G. S. Sales, Y. Huang, "Self-Induced Absorption of High Power HF Radio Waves", presented at the Suzdal Meeting on Ionospheric Modification, Suzdal, Russia September 9-12, 1991.

G. S. Sales, "The Investigation of Changes in the Ionosphere Caused by High Power Oblique HF Transmitters", presented at the URSI National Radio Science Meeting, Boulder, CO, January 1992.

3.2 Publications

J. Heckscher, G. S. Sales, I. G. Platt, Y. Huang, D. M. Haines, "Evidence of Ionospheric Changes Caused by a Powerful OTH HF Transmitter", Proceedings of the OTH Radar Technology Conference, Hanscom AFB, MA, January 1992.

Y. Huang, G. S. Sales, I. G. Platt, D. M. Haines, J. L. Heckscher, P. Kossey, "The Investigation of Changes in the Ionosphere Caused by High Power Oblique HF Transmitters", Abstracts of the URSI National Radio Science Meeting, Boulder, CO, January 1992.

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", Radio Science, Vol. 26, No. 4, pp 931-942, July-August 1991.

J. T. Ralston, J. A. Weitzen, and J. C. Ostergaard, "Distribution of Underdense Meteor Trail Durations and Duty Cycle and Applications to Meteor Scatter Communication System Design", Radio Science, Vol. 28, No. 5, pp 747-757, September-October 1993.

J. A. Weitzen, S. Bourque, J. C. Ostergaard, P. M. Bench, and A. D. Baily, "Distributions of Underdense Meteor Trail Amplitudes and its Application to Meteor Scatter Communication System Design", Radio Science, Volume 26, No. 2, pp. 451-458, March-April 1991.

3.3 Scientific Reports

G. S. Sales, Y. Huang, "Observation of Ionospheric Modification Using High Power Oblique HF Transmissions", PL-TR-92-2079, Scientific Report No. 1, June 1992, ADA258706.

G. S. Sales, "Ionospheric Modification by High Power, Obliquely Propagated HF Radio Wave Transmissions, Part I - Experimental", PL-TR-93-2171, July 1993, ADA273746.