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Ionospheric Modification by Powerful Radio Waves – the ~~2nd~~ Suzdal Symposium (2 th) HELD IN TROMSO, NORWAY ON SEPTEMBER 1988.

George J. Morales

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Presentations given at this conference, held in September 1988 at Tromso, Norway, are discussed. Topics include: parametric decay and Langmuir turbulence, electromagnetic emissions, satellite/rocket studies, large-scale density cavities, artificial ionization, and oblique heating. The author also reports on associated visits to EISCAT and the Swedish Insitute in Uppsala.

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Ionospheric Modification by Powerful Radio Waves–the 2nd Suzdal Symposium

Second Suzdal Symposium

Nature of the Meeting. The "Second Suzdal URSI Symposium on Ionospheric Modification by Powerful Radio Waves," held in Tromso, Norway, September 1988 was sponsored by the International Union of Radio Science (URSI), National Academy of Sciences of the Soviet Union, Norwegian Research Council, University of Tromso, Max-Planck Institute for Aeronomy, the US National Science Foundation (NSF), and the European Office of Aerospace Research and Development (EOARD). Conference cochairmen and principal organizers were Drs. V. Migulin of IZMIRAN, USSR; and W. Gordon of Rice University. The scientific program was chaired by Dr. P. Stubbe of Max-Planck Institute for Aeronomy, West Germany, and the local arrangements committee by Professor A. Brekke of the University of Tromso, Norway.

The purpose of these biannual meetings is to bring together leading researchers (theoreticians and experimentalists) in the ionospheric modification area from Western countries with their counterparts from the Soviet Union. The goals are to present and review recent progress in the field, to assess priorities for future investigations, and to develop working collaborations and exchanges between Western and Soviet scientists. The name of the conference is derived from that of the town of Suzdal, a small resort area near Moscow, where the first joint Western-Soviet meeting took place in 1986. According to Dr. Migulin, an all-Soviet Suzdal meeting had been held prior to 1986. At the urging of Drs. Miguline and Gordon in 1986, the concept of a biannual Western-Soviet exchange meeting named "Suzdal" was born. The meetings are to be held on a rotating basis between a Western site and Suzdal or an equivalent resort area in the Soviet Union. This concept has gained tremendous support from researchers worldwide and it appears that this conference may become the premier forum for scientific presentations in this field in the years ahead. Preliminary plans were drafted in Tromso for holding the next meeting in the USSR during (tentatively) of September 10-14, 1990.

Local Environment. The city of Tromso, located on a small island off the west coast of Norway, just above the Arctic Circle, has a population of approximately 50,000 inhabitants and is the economic, educational, and administrative center for northern Norway. It is located in extremely attractive surroundings consisting of a deep-water port surrounded by steep mountains and connecting to adjacent fjords. On clear nights spectacular auroral displays can be seen overhead. The principal source for the local economy is fishing off the coastal waters, and I was informed that presently there are severe problems related to over-fishing and unprecedented growth in the population of seals.

The other major source of activity in the city is the University of Tromso (about 2,000 students and 50 faculty members), which is the northernmost branch of the excellent Norwegian university system, and an outgrowth of the Auroral known for its pioneering work (Birkeland, Stormer) in auroral observations. Many of the researchers have joint appointments between the university and the observatory, and strong groups exist in applied mathematics related to ionospheric modification and space plasma physics (E. Mjolhus, C. Dysthe, A. Brekke), basic laboratory experiments in plasma physics (J. Trulsen, R. Armstrong), optical observations, and overall support for radar studies with EISCAT (the ionospheric diagnostic radar complex in Tromas [more on this later]).

The participants were accommodated in the modern Iscandic Hotel where the scientific meetings were also held during the mornings and afternoons. The excellent (but rather expensive) hotel is on a hillside within a mile of the small Tromso airport, but significantly distant from the center of town. This arrangement provided a natural setting for strong interaction among all participants at all times. It was the consensus that many valuable informal discussions resulted and that important and lasting personal contacts developed out of this meeting thanks to the good planning efforts of the local committee.

Participation. There were 54 registered participants. These included: 16 Europeans, 1 Canadian, 9 Soviets, and 28 from the US. The large US contingent included several observers (2 USAF, 1 NSF, 1 Atlantic Richfield Co.), as well as a recent Soviet immigrant (Mihlik).

Although the Soviet delegation constituted a small fraction of the total number of researchers in this field in the USSR, it was the consensus of the Western participants that this was an unusually large group composed of senior leaders from the major ionospheric research centers. By contrast, the larger US representation constituted nearly 90 percent of the active researchers in the states – a far smaller research community than that in the USSR.

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Dominant members in the Soviet delegation were the following: A. Gurevich (Lebedev Institute), the leading Soviet theorist in this field; V. Vas'kov (IZMIRAN), a former close collaborator of Gurevich and recently named head of ionospheric modification activities at IZMIRAN; V. Kim (IZMIRAN), former theoretical student of Gurevich and presently the leading experimentalist in charge of diagnostics at IZMIRAN; and V. MIGULIN (IZMIRAN), a pioneering early experimentalist in this field and senior spokesman for the Soviet delegation.

The European participants were primarily from three groups. As expected, they were from the local University of Tromso; from the Max-Planck Institute for Aeronomy at Lindau, West Germany; and from the Swedish Space Institute at Uppsala, Sweden. Although France and England contribute a significant fraction (25 percent each) to the operating budget of EISCAT (the ionospheric diagnostic radar complex in Tromso), only two representatives from England (one a graduate student at Uppsala) were present and none from France. It is likely that this low level of activity is a result of the heavy concentration on fusion problems by the plasma-trained scientists in these two countries.

Scientific Program. A total of 45 oral presentations (15 minutes for presentation, 5 minutes for discussion) were tightly scheduled during mornings and afternoons and spread over 3-1/2 days. One full day was devoted to visiting the experimental facilities EISCAT and HEATER (their HF heating facility), and the last afternoon was devoted to assessing future developments, Soviet collaborations, and planning for the next conference.

The topics discussed were arranged into the following categories:

- Description of ionospheric modification facilities and associated diagnostic instrumentation
- Review of recent results
- Modification of the lower ionosphere; generation of ELF/VLF waves
- Miscellaneous theoretical investigations
- Large-scale F region perturbations
- Artificial ionization
- Oblique heating.

A selected overview of some of the presentations made under these categories follows. A personal assessment is made at the end.

Description of Facilities. Professor T. Hagfors (Cornell University and Director, Arecibo Observatory) gave a detailed account of the layout and present capabilities of the HF heating facility at the Arecibo Observatory in Puerto Rico. This national facility is operated by Cornell University under contract from NSF. The antenna array was built in 1980 at Islote, a marsh 17 km northeast of the Arecibo Observatory, where the large radar dish used for diagnostics is located. The antenna consists of 32 elements and is divided into two separate east-west sectors that are individually driven by two transmitters each. Phase delays can be added to each of the sectors to generate predominantly 0 or X polarizations. Present capabilities permit a maximum total radiated power of 400 kW (100 kW per transmitter) over a discrete set of frequencies in the 3- 9-MHz band. The antenna has a theoretical gain of 25 dB, thus resulting in a maximum effective radiated power of 120 MW. Some of the shortcomings of the system are the lack of beam steering capability, excessive side-lobe generation, and operational unreliability resulting from the use of open finite wire conductors to deliver the power to the individual arrays. It is the feeling of several scientists who use this facility that the hardware is behind what can be done with present-day technology (e.g., no use of computer controls) and that an effort should be made to upgrade the HF system to explore many interesting developments that were presented at the conference.

The existing HF facilities and diagnostic capabilities used in the Soviet Union for ionospheric modification studies were catalogued by Dr. V. Kim (IZMIRAN). The oldest facility, in operation since 1961, is in Moscow and has a large ERP of 1 GW for short pulses of 500 μseconds at 50 Hz and operates in 0 and X polarizations.

There are several antenna systems capable of CW operation at Gorky and covering the frequencies of 1.2, 2.5, 3.3, and 4.5-9.3 MHz. The most advanced antenna in Gorky is named SURA; it has 300x300 m^2 area, it can be steered electronically and can operate CW at ERF of 5-300 NW in 0 and X polarization. Other facilities include Dyushanke (in the south), operational since 1983 (4-5 MHz, ERP = 9 MW); Murmansk, operational since 1976 (3.3 MHz, ERP = 10MW); and Kharkov, operational since 1986 (5 MHz, ERP = 20 MW, pulse of 2.5 μseconds at 100 Hz).

According to Kim, the only incoherent backscattering (Thomson) radars used in conjunction with HF heaters are located in Kharkov (within 3 km of the HF facility) and operate in VHF (2 meters, 2 MW, 70- to 100-seconds pulse), and UHF (30 cm, 3 MW, 200-seconds pulse). An ion line return obtained with these radars was shown by Kim but no physics details were presented. It appears that funding for this facility comes from non-scientific sources, thus its results are not readily available.

Kim sketched the principles of a new Doppler and phase diagnostic he has developed. The idea is essentially to use a swept transmitter in the frequency range 1.5-3.0 MHz, with bandwidth of 1 kHz, time delay of 1 second and time resolution of 1 second. He is very proud that this hardware, when coupled with a software package they have developed, yields height resolutions of 20 m. Apparently the key to their method is a sophisticated algorithm developed by a Soviet mathematician that solves the inverse problem using as input the measured amplitude, Doppler shift, and time delay. No details about the algorithm were given or how they differentiate between scattering and absorption when a single receiver is used (as they are apparently doing).

From discussions by Kim of various diagnostic techniques used in the Soviet Union, it became apparent that they rely heavily on test wave diagnostics, partial reflection, and ionosonde measurements to investigate the HF-ionosphere interaction. The lack of Thomson radar studies prevented the Soviet delegates from participating in the many extensive and controversial discussions concerning the structure, variability, and spectrum of the artificial plasma lines generated by HF heaters and routinely observed at Arecibo and Tromso.

The HF heating facility known as HEATER, located at Ramfjordmoen (an hour's drive from Tromson), was described verbally (no viewgraphs) by H. Kopka (Max-Planck Institute). This facility has been built, operated, and managed by the Max-Planck Institute for Aeronomy under the leadership of P. Stubbe and has been used since the early 1980's to do pioneering work in ELF and VLF generation, stimulated electromagnetic emissions (SEE), and generation of field aligned irregularities. The facility is extremely well engineered and can be run by one full-time technician on site. Originally the system consisted of two separate narrowband antennas ($\sim$24 dB gain) at transmitter powers of 1 MW. The lower frequency antenna array (2.76 MHz), used extensively in ELF-VLF modulation experiments, was destroyed by a severe storm over a year ago and is no longer in operation. The array is being rebuilt and within a year is expected to become operational and merged with the surviving antenna into a single system known as SUPERHEATER, which will operate at higher frequencies (5.3 MHz) at a power level ERP = 1.5 GW. The HF beam can be tilted in the north-south direction by 30°.

It was announced by the German group that the Max-Planck Institute plans to discontinue operating the HF facility in 1992 and that they are at present actively seeking another organization to take over operations. It was the consensus of the participants at this meeting that every effort should be made to ensure that the new SUPER-HEATER continues to operate beyond 1992. It appears natural that the multinational organization EISCAT (in charge of the diagnostic radars on site) should assume this role, but no definite plans have been made.

A.Y. Wong (UCLA) briefly described the HIPAS facility located near Fairbanks, Alaska, which is presently used for ELF studies, second harmonic electron cyclotron resonance heating at 2.85 MHz, and density modification. Present capabilities are CW operation at 100 kW per transmitter (eight available) with an antenna gain of 18 dB. A proposal is being made to enlarge the facility to 100 GW of pulsed power. A. Ferraro (University of Pennsylvania) was scheduled to present results of ELF studies at this facility, but unfortunately he was not able to attend the meeting.

Review of Recent Results. A. Gurevich (Lebedev Institute) presented a hastily put together overview of Soviet investigations spanning over a decade. He emphasized from the outset that the problem of HF-ionosphere interaction is extremely complicated and that "we need nonlinear plasma theory to understand it." The most exciting of the results pertain to recent findings that the upper-hybrid resonance (to a large extent neglected in most studies) is playing an important role in the absorption of HF energy, but the details are not clear. It is noteworthy that mounting evidence presented by other groups (including myself) suggest that the upper-hybrid phenomenon may be the most important topic for investigation in the near future. A brief account was given by Gurevich of the use of HF heating to determine the lifetime of electrons undergoing recombination stimulated electromagnetic emissions at altitudes around 180 km. Mention was made of (SEE) measurements (not indicated where) that showed upshifts as large as $\Delta f \sim 192$ kHz from the frequency of the HF heater. Many investigations are being made in Gorky concerning the spatial structure of ionospheric turbulence generated by the HF heater. Gurevich likes using detailed studies of ELF fluctuations to infer the properties of ambient fluctuations. It was mentioned that moving phase perturbations (of the HF heater) have been demonstrated to be an effective method for generating ELF. Gurevich also reported that VLF waves have accelerated H^+, $H_e{}^+$, and O^+ ions out of the ionosphere and that electrons can be accelerated by topside sounders.

Since two separate sessions were scheduled at this meeting concerning future ionospheric ionization and oblique heating experiments, Gurevich reminded the audience that since 1977 oblique incidence experiments in the USSR have generated strong ionospheric disturbances. He also explained that artificial ionization has been extensively studied in the USSR since the early 1970's and that he had brought along with him a copy of a book (in Russian and authored by him) in which a summary of the experimental and theoretical results is presented. He offered the book for publication in English, and several of the US delegates promised to help in this activity. It is evident from Gurevich's talk that he is extremely interested in applications of artificial ionization and that he would like to hold a small workshop in the USSR with strong US participation.

P. Stubbe (Max-Planck Institute) presented his assessment of recent studies performed at the Tromso facilities. Since EISCAT now has made the VHF radar (224 MHz) available for experimentation, many of the studies have shifted emphasis in order to utilize this diagnostic. He reviewed the impressive amount of data pertaining to ULF-ELF generation over a broad frequency range of 10^{-2} to 10^4 Hz, and tried to correlate the observations with simple electrical circuit models (elaborated further in a presentation by M. Ritveld, Max Planck Institute) of electrojet modifications. It is found that over a restricted frequency band agreement can be obtained, but no unified model can account for the amplitude of the signals over the entire experimental band. He reported that large-scale density depletions (thermal cavitons) have been observed to be generated at levels of $|\delta n|/n_0$ ~ 10 percent. The 224-MHz radar indicates overshoot of the ion line after JF turn-on, but not on the plasma line. By contrast, the 933-MHz radar docs show a plasma line overshoot within 1 second of turn-on. Furthermore, he emphasizes that the 224-MHz return does not exhibit a zero frequency feature, and that the location of the plasma lines observed is about 10 km lower than the height of the plasma resonance. This feature is to be contrasted with recent observations made in Arecibo that indicate plasma lines located near the plasma resonance layer.

Stubbe emphasized that he believes the origin of SEE is due to inverse mode conversion of Langmuir waves into electromagnetic waves, but that a puzzle exists in the data that cannot be explained by existing theories, namely the presence of a continuum of emission at frequencies larger that the frequency of the HF heater and extending beyond 200 kHz. He reiterated his belief that Langmuir wave collapse does not occur in the Tromso experiments.

Parametric Decay and Langmuir Turbulence. One of the more lively technical discussions held at this meeting pertained to the interpretation of the spectral features of the backscattered Thomson diagnostic signal in the neighborhood of the electron plasma frequency – i.e., the enhanced plasma line. Many workers in this field have believed since the early 1970's that the signals were associated with parametric decay instability daughter waves triggered by the ground-launched HF wave. It has been proposed by several investigators that various complex features of the measured spectrum result from multiple cascade processes (sequential parametric instabilities) of the type described by weak-turbulence theories; many of the older researchers have accepted such a model for several years. However, during the late 1970's a quiet revolution developed within the basic plasma physics community that is more closely associated with laboratory experiments. The essence of such developments is that large-amplitude Langmuir waves behave quite differently from what is predicted by weak-turbulence theories. In fact, strong Langmuir turbulence evolves into intense localized fields that are trapped inside small-density cavities (a few cm to 1-m size in the ionosphere) generated by the self-consistent pondero-motive force. In a loose sense, the phenomenon is referred to as "collapse," but in reality there are two routes to collapse, namely, via self-modulation (in the absence of an external driver) or directly driven through a strong JF pump wave. Because the frequency spectrum of an individual localized field can differ significantly from the average plasma frequency, and the possibility that the Thomson radar may be sampling a large number of such cavities having partial correlation, it is expected that if Langmuir collapse occurs that rich spectral features should be observed. Of course, the detailed prediction of a spectrum is rather complicated (and perhaps unrealistic) within this framework, but nevertheless it is expected to yield qualitative features consistent with the observations. So the dilemma is what to believe – the old weak turbulence picture or the more modern collapse model. Unfortunately, at the present time this debate is being approached with religious zest, with groups attesting that every observation proves their preconceived version of how the HF wave modifies the ionosphere. It is my opinion that the discussion of the issues has become overly simplified. A realistic assessment of the problem must incorporate the important role played by the nonuniformity of the ionosphere near the cut-off and resonance point of the HF wave; current analysis of the controversy, however, neglects such a feature.

D. Dubois (Los Alamos National Laboratory) expressed his strong belief that Langmuir collapse is the dominant process in the HF-ionosphere interaction and that he had changed his mind about the relevance of his early work on parametric instabilities. These views were supported by lengthy computer solutions of nonlinear fluid equations in a uniform medium which show bursts of localized fields followed by remnant cavities. A local caviton model consisting of a localized field and a long scale field is used to generate numerically the frequency spectrum at fixed wavenumber k. This model yields a free mode feature having frequency higher than that of the HF pump, thus resembling a subtle feature recently observed in some field experiments.

A review of many different studies of plasma line spectra was given by J. Fejer (University of California, San Diego), who concluded that the only feature that can be claimed to be well understood is that for low HF power (presumably below the parametric instability threshold), where one observes barely enhanced plasma lines in which the ambient ion noise spectrum is superimposed. He acknowledged that what is not well understood is the spectrum for HF powers above threshold, and that the dilemma is why the strongest plasma line return in recent high-resolution experiments comes from high altitudes (presumably near the plasma frequency). He presented new data obtained at Arecibo with a 46.8 MHz diagnostic radar and admitted that clear evidence exists for direct conversion of the HF wave into Langmuir waves due to irregularities. This is a mechanism observed several years ago by my colleagues and I using the 430 MHz radar, but some investigators have been reluctant to accept it.

D. Muldrew (CRC, Canada) elaborated on his long-standing belief (based on early 1970's data) that all the puzzles associated with the slow time dependence (e.g., overshoot) and spectrum of the plasma line return can be understood by invoking the existence of field-aligned density ducts. He described ray tracing calculations of Langmuir waves experiencing local growth due to parametric pumping inside a prescribed cylindrical duct having 25-m diameter, 10-km length, and 3-percent density depression. While some of the scientist believe that some sort of duct structure exists, there is general skepticism about the arbitrariness of the parameters chosen (questioned by Gurevich). Clearly, a first principles calculation of this interesting effect is warranted.

S. Kuo reported an elaborate analytical model based on renormalized resonance broadening theory to explain the observed plasma line overshoot – i.e., long-term decrease of the amplitude of an excited Langmuir wave. The idea is that electron diffusion by large-amplitude plasma waves produces an anomalous damping that competes with the weak-turbulence cascade processes that feed the particular wavenumber being sampled by the diagnostic radar.

Various features of the plasma lines detected by the EISCAT VHF radar that recently became operational at Tromso were described by H. Kohl (Max-Planck Institute). He clearly observes that plasma lines grow rather quickly, i.e., within 3 msec (also reported by F. Djuth [below]) of HF turn-on, and their first time is independent of HF power. Both features seem to contribute further evidence for the universality of the direct conversion process. There appears to exist a lack of correlation between the ion line and the plasma line, and while the damping of the plasma line can be quantitatively explained in terms of electron-ion collisions that of the ion line can not. There is also evidence for plasma lines at frequencies higher than that of the HF and are reminiscent of the free modes seen in the numerical studies presented by Dubois. However, the experimental signals are observed at relatively low power, so their connection to strong Langmuir turbulence is not obvious. A significant asymmetry in the amplitude of the up-shifted and the down-shifted plasma lines is detected as the HF beam is scanned in the north-south direction; no explanation for this phenomenon is available.

T. Hagfors (Cornell University) reported preliminary attempts to implement in Tromso the chirping technique that he and collaborators have successfully used in Arecibo experiments to obtain spatially resolved plasma lines. It appears that the Tromso results are different from those in Arecibo (where signals from 2 different heights are claimed to be observed) because the spectra do not correspond to heater enhanced or natural plasma lines. In fact there are spectral features present at 200-300 kHz above the HF frequency, thus complicating the interpretation of the chirping method. Hagfors claims that the observed ion line is transient and may be related to Z-trace phenomena. Some of these unexplained features were catalogued by Kohl, who reiterated that signals substantially above (and below) the HF frequency are often observed and that large ion lines are excited but are unrelated to parametric processes.

Electromagnetic Emissions. One of the more exciting developments in the HF ionospheric modification area in recent years has been the observation of stimulated electromagnetic emissions (SEE). They occur over a broad frequency interval around the frequency of the ground-launched HF wave and exhibit unexpected spectral features quite different from those observed in Thomson radar backscattering from plasma waves. The great interest in SEE Is that it provides global information about the entire HF-ionosphere interaction, not just what occurs at one particular wavenumber (as the Thomson radar does). The measurements are relatively simple and inexpensive and can be made with significant spectral resolution. At present the only serious drawback is the lack of spatial resolution, a feature which requires multiple receiving stations.

Bo Thidé (Swedish Space Institute), who has made pioneering measurements of SEE, described the latest results of a campaign in Tromso in May 1988. His technique consists of recording the time series of the skywave with an array of portable antennas in a radio-quiet valley near the HEATER facility in Tromso. A broad upshifted maximum above the HF pump frequency (f_{HF}) has been systematically investigated by changing the pump frequency. It is claimed that the frequency of the emission is well explained by the expression $2f_{HF}$-n f_{ce}, where f_{ce} is the electron cyclotron frequency and n an integer. Thidé emphasizes that a clear relationship to cyclotron harmonic phenomena is observed from the data. T. Leyser (also of the institute) and Thidé are working on an involved four-wave process to explain this emission. Thidé also mentioned that similar features were also observed in experiments at Arecibo but the signals were much weaker there.

Another important feature observed by Thidé's group that may change the present understanding of the HF-ionosphere interaction is a bump at a frequency lower than f_{HF} by precisely the lower-hybrid frequency. As the value of f_{HF} is scanned across nf_{ce} (within a few kHz), a sharp change in the amplitude of this emission occurs. Although no definite quantitative model has been developed, Thidé and collaborators believe that direct conversion of the ground-launched HF on ambient strations leads to excitation of the upper-hybrid resonance. Leyser elaborated in a separate presentation on a model based on the decay of an upper-hybrid wave into an electrostatic lower-hybrid and an electromagnetic wave to explain the observations.

W. Gordon and S. Noble (also from Rice University) briefly described results of measurements made in Mona Island aimed at detecting low-frequency signals generated by beating two HF pump waves launched by the Islot facility (near Arecibo). Measurement made during 1987 and recently in May 1988 with beat frequencies in the range of 1 Hz to 1 kHz exhibit strong variability. They stated that the results are very different from those previously reported in the literature by Ganguly and Papadopolous. Ganguly was present during this discussion and gave indications that he would not strongly defend his earlier results at this time.

N. Gorokhov (Polar Geophysical Institute, Murmansk, USSR) reported on a recent collaboration with the Max-Planck Institute group. An attempt was made at Murmansk to detect the nonlinear generation in the ionosphere of an electromagnetic signal at the second harmonic of a wave launched from Tromso. After several checks on possible spurious generation of second harmonic signals, the Soviet group concluded that they have detected a signal of true ionospheric origin, but that more data is needed and they hope to continue the collaboration.

V. Trakhtengerts (Institute of Applied Physics, Gorky, USSR) described theoretical studies of the possibility of using HF heating to modulate the conductivity in the E region and thus excite low-frequency (~3 Hz) Alfven vortices. He recommends using two HF beams displaced in space to establish a 2- km wavelength that would resonate with the vortices. He calculated the threshold value of change in electron temperature required for the effect to be observable and concluded that the HF facilities in the USSR do not have enough power to perform this experiment.

Satellite/Rocket Studies. R. Benson (NASA/Goddard) described results obtained with the Canadian satellite program Alouett/ISIS, in which a topside sounder was operated at 400 W in the 0.1- to 20-MHZ band. He emphasized that the power density of these heaters corresponds to *in situ* values comparable to that of ground-based HF facilities. He described extensive evidence that suggests that electron Bernstein waves, cyclotron harmonic signals, and upper-hybrid resonances are readily excited.

A timetable of the various US satellite/rocket programs was presented by P. Rodriquez (NRL), and he indicated the possibility of fly-by experiments in Arecibo during 1991 by the CRRES satellite. It was acknowledged that data from such a study may contribute valuable information to large-scale modification studies.

J. Chugunov (Institute of Applied Physics, Gorky) described related theoretical, laboratory, and rocket studies based on the premise that cold-plasma resonance cones excited by a loop antenna can generate substantial ionization and thus produce controllable plasma in the ionosphere. A rocket launched in June 1986 from a Soviet ship in the Norwegian Sea carried a loop antenna and support diagnostic equipment to test this idea. The experiment appears to be very interesting, but because of the speaker's poor English, not many details were conveyed. It is observed that when the RF antenna is turned on, a large electron flux develops at energies larger than 2 keV. Downstream from the antenna, along connecting magnetic field lines, a plasma is formed as evidenced by photometer signals synchronized with the RF pulse.

Large-Scale Density Cavities. One of the more exciting and unexpected findings in the ionospheric modification area over the past 2 years is the formation of extremely large-density depletions ($|\delta|/n_o \sim 50$ percent) having scale lengths on the order of 10 km. These cavities result from the pressure imbalance along the earth's magnetic field due to intense electron heating produced by the HF wave near its reflection layer. The reason these results are so spectacular is the large magnitude of the depletions – an effect which is only observed in late nighttime ionospheres (i.e., after 11:00 pm local time). For daytime and early evening conditions, the relative magnitude of the density cavities is observed to be less than 10 percent, a figure which can be explained with analytical models and is consistent with the result of transport code analysis. Although the detailed reason as to why a late nighttime ionosphere is required is not yet known, the results presented at this conference unequivocally attest that the phenomenon is reproducible and not an instrumental or diagnostic artifact. In addition, a growing body of experimental results indicate that thermal cavitons exhibit a universal time asymptotic steady-state.

L. Duncan (Clemson University) reviewed his early results in which deep cavities were first observed, and systematically explained how the ambiguity in the Thomson radar return concerning density changes and temperature increases could be resolved. By studying the remnant cavities after the HF is turned-off, he can place a lower bound on the depth of the cavities (which in many cases is in the range $|\delta n|/n_o \sim$30-50 percent). Examining the return signals while the HF is on gives an upper bound on the temperature increases on the order of $\delta T_e/T_e \sim 2.5$. Duncan also described important results of a January 1987 campaign at Arecibo in which a detailed study was made of how the deep-density cavities relax towards the ambient equilibrium profile after the HF is turned off. It is evident that conventional collisional transport cannot explain the observed behavior, which seems to be associated with a series of stick and slip processes (akin to removing and adding density layers) rather than diffusive flow.

In my own talk, I presented a combination of analytical, computational, and experimental results obtained during May 1988 at Arecibo. A detailed comparison between a time-dependent transport code and a steady-state model proposed by Vas'kov and Furevich was reported. The simpler model is found to overestimate the depth of the cavities by a factor of 2. Correcting for this overestimate, it is found that for present experimental facilities the maximum attainable $|\delta n|/n_o$ during daytime conditions is less than 10 percent, a result which is consistent with reported observations in high (Tromso) and mid-latitude (Arecibo) experiment. A ray tracing study in prescribed field-aligned density channels illustrates the reason for the observed narrowing and northward shift of the heating pattern produced by the HF. Essentially, the 0 mode rays are turned around on the high-altitude side of the cavity, thus producing strong field-aligned heating that erodes into the ionosphere until the maximum critical density falls below the HF frequency (hence yielding the universal steady-state). Results of the Arecibo campaign include formation of cavities by several different HF frequencies, narrowing and northward shift of the heating pattern, intense rapid heating in preexisting density channels, and evidence for upper-hybrid resonance phenomena.

Results obtained in Arecibo during 1987 were presented by F. Djuth (Aerospace Co.). He stated that his previous objections concerning the reality of deep-density cavities were satisfied and that he had no disagreement with the material and interpretations presented by Duncan and myself. He explained that his own data when suitably corrected, as indicated by Duncan, yields density depletions of $|\delta n|/n_0 \sim 26$ percent. His earlier report of observed large ion temperature increase was traced to a problem with the fitting computer program, and he now states that T_i does not change very much. He strongly advocates a model for cavity relaxation in which energy is stored upwards (more than 103 km) along a flux tube and it returns to the F region on a time of several minutes after the HF is turned off.

F. Honary (University of Leicester, UK) described a large-scale-density cavity experiment performed in Tromso during February 1987 in which the WHF EISCAT radar was used to measure the density depletions along the earth's magnetic field (not possible at Arecibo). A maximum $|\delta n|/n_0$ less than 10 percent is found, but the values are larger than the prediction of a transport code study in which an ad hoc delta function heat source is used. She concluded that strong anomalous absorption is responsible for the differen

M. McCarrick (UCLA) briefly stated that experiments performed with the HIPAS facility in Fairbanks have produced density depletions $|\delta n|/n_0 \sim 30$ percent, but are the result of density clamping during local sunrise when the HF frequency is matched to the maximum critical frequency.

Measurements of enhanced airglow made with a delicate CCD camera and ensembled into a movie presentation were described by P. Bernhart (NRL). The data was taken during January 1987, when large-density cavities were observed. It is found that the spot where the peak airglow enhancement occurs moves in time and its location is claimed to be correlated with the motion of the HF footprint – i.e., the narrowing and northward shift I described. The picture that emerges is that the large-density cavities tend to concentrate the deposition of HF energy in a narrow flux tube along which fast electrons are generated. The long time-scale motion of the enhanced airglow is thus a combination of ambient drifts and HF beam-rearrangement due to density depletions.

Artificial Ionization. Several presentations were made by US scientists pertaining to artificial ionization, primarily in a laboratory environment but with ionospheric applications in mind. These discussions do not fall within the central interests of the HF-ionosphere modification community, but are certainly of interest to Furevich and his collaborators; hence, the idea of holding a separate meeting on this subject in the Soviet Union seems well justified.

S. Kuo reported small-chamber studies with S-band to investigate Bragg scattering from plasma layers. K. Papadopolous (University of Maryland) reviewed various models that describe RF breakdown in the earth's atmosphere at altitudes of 60-90 km. He concludes that the best regime is obtained with operation at 100 MHz and power densities of 10 kW/m^2. T. Armstrong (Los Alamos Laboratory) discussed various ionization phenomena obtained with microwaves in a laboratory experiment. CCD pictures of plasma filaments are used to quantify their dependence on fill pressure and pulse length. Using the laboratory results he assessed the feasibility of utilizing S-band Klystrons, of the type developed at the Stanford Linear Accelerator (SLAC), to perform ionospheric experiments at Arecibo. M.C. Lee (MIT) described observations of C-band radar scattering from lighting-induced filaments and attempted to compare the results with simple models.

Oblique Heating. G. Sales (Lowell Institute) described previous failed attempts by his group to diagnose modifications of the ionosphere caused by high-power (ERP ~ 10 GW) obliquely propagating HF waves (~ 10 MHz). He described an upcoming experiment in which the HF wave is to be radiated eastward from Delano, California, and to be received at Shreveport, Louisiana. The radiated power is expected to be on the order of 250 KW and the antenna gain in the range of 90 db. Modeling studies by E. Field (Pacific Sierra, Los Angeles) indicate that density modifications on the order of 3 to 4 percent of the ambient density and 50-percent temperature changes should occur. Preliminary testing is to begin in January 1989, and full-power experiments are scheduled for 1990.

After Sales talk, A. Gurevich emphasized that for oblique heating experiments, the effect of self-focusing on existing large-density fluctuations is an essential point. As he said: "It is in a statistical sense for practical reasons."

Personal Assessment. This conference is a significant landmark in the study of the HF-ionospheric interaction. It conveyed the excitement that new interesting effects, such as changes in large-scale densities (thermal cavitons), stimulated electromagnetic emissions, and upper-hybrid phenomena remain to be explored. A lot of good science is anticipated to come out of related studies over the next 5 years. The conference also marks an important transition from early qualitative models to a new era in which recent developments in nonlinear plasma theory are fully integrated into the interpretation of experimental results. It is significant to note that this transition is accompanied by an influx of younger workers into the field.

It is the consensus of the participants that an improvement of existing experimental facilities is certainly warranted and that more support for theoretical and modeling studies is needed in order to keep pace with the plethora of unexpected observations.

In the years ahead, knowledge gained from the HF-ionospheric interaction is expected to yield new possibilities for actively exploring the ionosphere-magnetosphere coupling. Some participants (such as Gurevich and Thidé) suggest developing high-power radars in the range of 10-50 MHz for this purpose, and this may be the ultimate direction. However, in my opinion, it appears that by using the thermal caviton phenomenon, relevant features, such as coupling to protosphere sources, can begin to be explored with existing facilities.

A Bonus – Visits to EISCAT and the Swedish Space Institute

EISCAT. On September 21, the symposium participants were taken by bus to the experimental facilities located in Ramfjordmoen, about a 1-hour drive from Tromso. These facilities are loosely referred to as EISCAT, which formally stands for European Incoherent Scatter Scientific Organization, and are supported and managed by a consortium of research institutions from Finland, France, West Germany, Norway, Sweden, and the UK.

Two separate radars are operated from Ramfjordmoen: a VHF radar (224 MHz, 2.5 MW) and a UHF radar (933 MHz, 1.5 MW). The VHF radar was originally designed to operate at 6 MW and to be bully steerable in the meridional plane, but it has run into several hardware problems that have limited its performance. Its steering capability, while technically feasible, has been negated in practice by the unfortunate fact that its radiation affects civilian activities (TV, telephone, etc.) it its neighborhood, so it is primarily used in field-aligned studies. As of our visit, it appears that the VHF operation has become more reliable and its use in support of HF heating experiments is to increase in the near future. This radar is, however, monostatic so it is used in the backscattering mode (just like the one in Arecibo).

The UHF radar has been in full operation since the early 1980's and consists of a 32 m parabolic dish that can be steered. This dish can be used also as a receiver (backscattering mode) or in conjunction with receiving sites at Kiruna (Sweden) and Sodankyla (Finland), thus allowing for tristatic measurements (e.g., determining the wave vector).

The radar facilities operate a total of 200 hours per year and are distributed between Common Programs (CP) and Special Programs (SP). The CP routinely gather data to monitor ambient ionospheric and auroral features in the altitude range of 70 to 1000 km. The SP are individual experiments of research groups (e.g., in support of HF heating). A general overview of results of the CP activities was given by C. La Hoz (associate director).

Although the EISCAT facilities are quite modern and impressive in their layout, it appears that they are very cumbersome for performing novel experiments that require on-line decision making. Their standard operation requires that a computer program must be prepared well in advance to the actual experiment. The program must instruct the radars what kind of pulse sequence to use and how the data is to be stored for future review. No easy access to analog signals is available and it is almost practically impossible to change experimental plans in the middle of a run. For this reason it is quite unlikely that unforeseen and difficult-to-repeat features associated with HF heating can be discovered with this facility. It is best suited for statistical analysis of highly reproducible features.

The control room of the HF facility HEATER is separately located (within a few hundred meters) from the control room of the radars. Although this situation is not as extreme as in Arecibo (17 km), it does require communication between experimentalists over the telephone. the HF control room is highly efficient and is fully computerized. However, a serious drawback is that it is managed and controlled separately from the radars, so experiments in which close coordination and on-line exploration are needed seem to be difficult to perform. The visitors were shown how tuning of the transmitters is performed from the PC controls, and a simple SEE experiment was performed using an on-site receiver antenna. Some of the features discussed by Bo Thidé were recognizable.

The Swedish Space Institute in Uppsala. During September 26-28, 1988, I visited the Uppsala branch of the Swedish Space Institute, formerly known as the Uppsala Ionospheric Observatory, to engage in more detailed discussions of SEE phenomena and to present a seminar on large density modifications.

The Institute is located 7 km southwest of the city of Uppsala in a rural area where several radio and radar antenna systems are located. The Uppsala branch is directed by Professor Rolf Bostrom and the headquarters of the national organization is in Kinura. The branch is closely associated with the University of Uppsala, and several graduate students perform their Ph.D. research while being employed as staff members of the Institute.

The University of Uppsala is the oldest in Scandinavia (founded in 1477) and enrolls nearly 20,000 students, approximately 3,000 of whom are graduate students. It awards about 140 Ph.D.'s a year and it has the largest mathematics and natural science faculties in Sweden. There have been five Nobel prize winners associated with the university and a strong international reputation in chemistry was developed under the leadership of Professor Svedberg.

The research program of the Institute covers space plasma physics – in particular, high-latitude ionospheric phenomena. Experiments are performed using sounding rockets and in conjunction with the Swedish Viking satellite. Groups at the institute use the EISCAT facility to investigate ambient phenomena as well as modifications produced by HF heating.

My host at the Institute was Dr. Bo Thidé, who leads a very active group of young investigators engaged in the study of SEE. The group consists of several technicians, two graduate students, a senior experimentalist (H. Derblom), and an applied mathematician (B. Lundborg). At the present time the group is analyzing data from a campaign at Tromso earlier this year, and are engaged in the formulation of analytical models to explain the various features observed. In particular, they are concentrating on processes in which the upper-hybrid resonance plays an important role. They are also developing mathematical techniques that provide an accurate description of the electric fields of the HF wave near the reflection layer.

Dr. Thidé is developing plans for constructing a high-power (ERP of several GW) 50 MHz radar in Kiruna. The radar should be steerable in order to sample the volume heated by the HF facility at Tromso, and, in addition, it is to be used as a field-aligned heater to investigate ionosphere-magnetosphere interactions. He is also improving the detectors used in SEE measurements and hopes to be able to develop a multiple-site diagnostic capability.

Without question the research performed by Thidé and collaborators is first-rate and makes the Uppsala Institute one of the leading centers in the world in the area of HF-ionosphere interactions.