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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking P.N.Lebedev Institute of Physics as follows: The contractor will develop the theory of ionospheric heating and quantitatively compare the Gurevich theoretical calculations (driven by measured input boundary conditions) to actual existing data. They will, jointly with PL scientists, design and implement experiments to iterate comparison of refined experiment to refined theory. The theory, the incoherent scatter radar data, and supporting observations will be used to pursue electron acceleration mechanisms.

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## Studies of Plasma Instability Process Excited by Ground Based High Power HF (Heating) Facilities

### ANNUAL REPORT

The active Heating Experiments (ionospheric modification by ground based high power HF transmitters) were performed in the US, USSR and more recently in Western Europe for over two decades (Utlaut 1970, Utlaut and Cohen 1971, Carlson et al 1972, Gurevich 1978, Stubbe and Kopka 1982). Heating experiments were used to reach understanding of various physical, chemical and plasma processes in ionosphere and to develop a variety of engineering applications (see Gurevich 1978, Migulin and Gurevich 1984, Carlson 1990). Significant results had been obtained but much still remains to be learned. New more powerful Heating Facilities are now under construction by the US Air Force to further push the boundaries of our knowledge of these processes.

It was found that used in modification HF power is sufficient to excite different type of plasma instabilities (Carlson et al 1972, Perkins and Valeo 1974, Vaskov and Gurevich 1975). One of the most significant new physical phenomena, discovered during ionospheric modification was the resonance instability leading to the generation of small scale striations which are plasma density depletions strongly elongated along the Earth's magnetic field (Utlaut 1970, Gurevich 1978). Recently such striations were also observed in Arecibo experiments *in situ* on board rockets (Kelley et al 1995). They have been seen as essentially local stationary depletions of plasma density $|\delta N/N| \sim 0.05$

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with scales of the order of 10 meters across and several kilometers along the magnetic field lines.

A nonlinear theory determining the conditions of existence and the structure of stationary striations has been recently developed (Gurevich et al 1995). The theory is in remarkably good agreement with the rocket observations (Kelley et al 1995). It's most significant prediction is a strong local enhancement of the electron temperature $T_e$ in the striations. Maximal electron temperature in the center of striations can reach the values $T_e/T_i \sim 3$ 5, average temperature ratios in a strongly disturbed region can be of the order $T_e/T_i \sim 2$ 3. Recent analysis done by Carlson and coworkers (Mantas and Carlson 1996) and Gurevich and Milikh (1997) showed that much of HF excited optical emission (previously attributed to electron acceleration) could come as a result of thermal accelerated electrons. Yet we still know from incoherent scatter radar plasma line data (Carlson et al 1982) that electron acceleration to well over 10 ev occurs.

The main goal of the project is to develop the theory of ionospheric heating and compare theoretical calculations to actual existing data. In accordance with these goals the following researches were fulfilled during the last year. Basing on the theory it was done a new refined analysis of the *in situ* observational data obtained on rockets what made it possible to determine the Fourier spectrum of striations developed in Arecibo heating experiments (Franz nee Aree, Kelley, Gurevich 1998). This spectrum was compared in details with the predictions of the recent theory by Gurevich et al. (1995) and with the multy-radar cross-section spectrum obtained previously in Platteville by Minkoff et al. (1974). This comparison from the one side demonstrated a strong similarity of the theoretical and experimental results. From the other side it showed some new important features of the observed spectrum which indicate the necessity to develop a refined theory. The new developed theory describes the existence of a very small-scale structure (determined by *self-oscillations of striations*), new self-focusing process (*bunching of striations*) and specific determined by large-scale of structuring striations in the low latitude ionosphere (*patches of striations*).

## 1 Self-oscillations of stationary striations.

A theory describing a nonlinear stationary state of striations was developed in Gurevich et al. (1995). Now we have studied the behavior of small disturbances of striations stationary state. The full system of equations, which describe the motion of electrons and ions and electric field disturbances inside striations was formulated and solved in linear approximation. The solution showed, that the drift-type waves could be excited inside striations. The disturbances are strongly elongated along the magnetic field: transverse dimensions are $\leq$ 1m, scales along magnetic field $\geq$ 500m. The possibility of excitation of these waves is affected strongly by the high electron temperature inside striations predicted earlier by the theory (Gurevich et al.1995). The excitation of drift-type waves means the existence of small amplitude self-oscillations of striations with the frequencies $f \geq (30-100)$Hz.

These oscillations, predicted by the theory, should be seen in observations of field aligned scattering of HF and VHF radio waves. And really in the base of the spectrum of HF radio waves($f \approx 50$MHz) scattered by striations at high power of heater wave one can see the characteristic Doppler width $\sim 50$ Hz (Korovin et al. 1982; Noble and Djuth 1990). The analysis of the striations Fourier spectrum, observed in the rocket measurements, and its detailed comparison with the theory of stationary striations (Gurevich et al. 1995) make it possible to establish the existence of analogous specific mode of oscillations with the frequencies of the same order(T. Franz nee Arce, Kelly, Gurevich 1998).

One can speculate that these observations support the existence of striations self-oscillations, predicted by the theory. These experimental facts could be considered also as indications of the high electron temperature inside striations.

## 2 The bunching of striations.

As was already mentioned above the plasma density is always diminishing inside striations. This fact is in a full agreement with the theory of stationary striations (Gurevich et al. 1995) and with the rocket observations by Kelley et al. 1995. It has important physical consequences. Because of this the average electron density is reduced during the excitation of a large number of striations, what results in a focusing of a pump wave $E_0$ and formation of a bunches of striations. But the enhancement of the field $E_0$ in the focusing region leads in turn to increasing of striations. Thus there is a close nonlinear connection between the striation formation and focusing. The bunches of striations together with self-focusing of a pump wave could form some "structuring" of a disturbed region in ionosphere.

We developed the theory of this new physical process: self-focusing of a pump wave on a large number of excited striations. The process is described by the following system of equations:

a)The wave equation for the propagation of ordinary radio wave in anisotropic and vertically inhomogeneous ionosphere.

b)The equations, describing density depletion $N_1(x)$ in one isolated striation.

c)The averaging of density depletion $N_1(x)$ over $x$ for a large number of striations and determining the dependence of the averaged density depletion $< N_1 >$ on the amplitude of a pump wave.

This system of equations is solved for the mostly simple case, when the radio wave propagates along the magnetic field. The form of a bunch of striations and the amplitude distribution of a focused on striations pump wave is obtained. The focusing is shown to be quite specific, significantly different from the usually considered electromagnetic wave self-focusing for isotropic medium in nonlinear optic.

The typical scale of the bunches of striations in ionospheric conditions is of the order (0.1-1)km. The bunching of these scales was observed in rockets measurements (Kelley et al. 1995). The same scales of a large inhomogenieties formed in ionospheric modifications were seen previously in different radio sounding experiments (Utlaut and Cohen, 1971; Gurevich, 1978).

The results of the theory described in sections 1 and 2 are prepared for publication in a paper "Self-oscillations and bunching of striations in Ionospheric Modification", which is given in an Appendix 1 to this report. The paper recently published in Physics Letters A 239, 385-392, 1998.

# 3 Effect of the nonlinear structuring on the propagation of radio waves in the ionosphere.

The effects of generation of striations and nonlinear structuring developed in modified ionosphere depends strongly on the inclination angle $\alpha$ between the Earth magnetic field and vertical direction. We study now the effect of inclination angle. If the inclination angle is small enough $\alpha \leq 20^o$ one can suppose, that striation formation, bunching of striations and nonlinear structuring is developed quite easy, close to the simplest case considered in section 2. Such conditions exist for Platteville, SURA, Tromso and HAARP facilities.

Quite a different situation is for a large $\alpha$ in low latitude ionosphere, for example, for Arecibo, where $\alpha \approx 40^o$. The possibility of a bunching and large scale structuring can strongly depend now on the concrete form of nonlinear structures, their angles with magnetic meridian plane and other parameters. The problem became much more complicated, than in the simple case, considered in section 2, and ask a modelling using a detailed numerical work. The modelling is based on the following main considerations. In order to excite striations and organize large scale nonlinear structures by the self-focusing of the pump wave on the bunches of striations two conditions should be satisfied simultaneously. First of all, to excite striations perpendicular to the magnetic field component of the pump wave at the upper hybrid level $E_\perp^{UH}$ should be large enough. This would lead to the strong absorption of the pump wave on striations in the vicinity of the upper hybrid level to support the existence of large scale irregularities (*patches*) inside which the pump wave should be trapped. In other words, the pump wave should be trapped by large scale irregularities and propagate inside them in the direction close to the magnetic field lines.

These conditions are not easy fulfilled in the low latitude ionosphere. To show the possibility of nonlinear structuring the following model calculations were performed.

## 3.1 The model of the large scale inhomogeneities

To choose a model of irregularities one should take into account the following. First of all, density perturbations in the magnetized plasma (ionospheric F-layer) should be field aligned as determined by the dominant transfer processes along the magnetic field. Second, the maximum absolute value of density depletions $|\langle N_1 \rangle|_{max}$ should occur at the region of maximum absorption of the pump wave, i. e. near its reflection level in the unmodified ionosphere. Finally, depletions fall off strongly enouph along the magnetic field lines.

The analysis of the averaged plasma density depletion structures fulfilled in the section 2 (see Fig. 4 of the paper A1), shows that density depletions inside bunches of striations have approximately constant value with steep boundaries in the horizontal plane.

Taking all this features into account we present each large scale irregularity by the following model formula

$$\langle \frac{N_1}{N} \rangle = n_0 \arctan[(ax_i)^2 + (by_i)^2] \exp[-(cz_i)^2], \tag{1}$$

where $(x_i, y_i, z_i)$ is the local coordinate system related to the individual irregularity ($z_i$-axis is along the magnetic field, $(x_i, y_i)$ is the horizontal plane). Density fluctuations (??) were normalized then to the 10% density depletion in the center by the appropriate choice of $n_0$. The centers of irregularities ($x_0^i$, $y_0^i$, $z_0^i = 1$) were chosen equidistant in the direction of their short axes. Several large inhomogeneities (normally 3 to 5) were supposed to exist in the modified ionospheric volume.

An elliptic form for the inhomogeneities (??) in the horizontal plane was chosen as an appropriate general anisotropic presentation. As it will be seen later from the results of calculations the trapping of rays at low latitudes when $\alpha \approx 40°$ (contrary to the high enough latitudes when $\alpha < 20°$) can occur only if the irregularities have rather large extent in the magnetic meridian plane because of the propagation effects.

## 3.2 Geometry of calculations

The geometry for the numerical calculations is shown in the Fig. 3 of the paper A2. The coordinate system is chosen in such manner that the $z$-axis is vertical, the horizontal $y$-axis lies in the magnetic meridian plane and the $x$-axis is orthogonal to it. Ionosphere begins at $z = 0$ while the source of radio waves is situated below it at $z = -z_0$, $x = y = 0$. Projection into the horizontal plane is shown in the Fig. 3b. Positive direction of the $z$-axis corresponds to the increasing height. For the given geometry negative direction of the $y$-axis corresponds to the north direction (positive - to the south direction), and positive direction of the $x$-axis corresponds to the west direction (negative - to the east direction). We will refer to these directions in the discussion. The center of the system of large scale inhomogeneities was chosen to be displaced in the north direction according to the propagation effects in the magnetized plasma and thus to be near the center of the radio wave beam at its reflection region. Inhomogeneities were normally supposed to be field aligned with rather large extension along the magnetic field, and substantially different characteristic size in the orthogonal directions in the horizontal plane, as it is shown in the Fig. 4 in A2; long axes of the horizontal cross-section of irregularities is supposed to be several times larger than the short one making an angle $\psi$ to the magnetic meridian plane. The necessity to choose such anisotropy will be explained in more details later in this Section.

The ambient density profile for the ray tracing calculations was chosen to be linear with increasing with height plasma density $v = z$, where $z$ coordinate is the height normalized to the characteristic scale of the layer $L$. In the ionospheric modification experiments the value of $L$ is typically about 50 km. Horizontal coordinates $x$ and $y$ were also dimensionless normalized to the same characteristic length $L$.

Plasma density was calculated according to (??) as the regular layer profile and the sum of perturbations caused by irregularities. The last were determined by the transformations to the individual local coordinate systems related to each irregularity. A similar procedure was used to obtain the density gradient.

Ray tracing was done for the pump wave beam of ordinary polarization of approximately 6° width which is typical for SURA ionospheric heating experiments. Calculations were performed using PV-Wave 6.02 Gear-Adams method with relative accuracy of $10^{-11}$. Radio wave propagation for the square grid of $20 \times 20$ equally spaced rays was calculated in each run for different parameters of irregularities. The pump frequency was chosen to be four times greater than the electron cyclotron frequency ($\sqrt{u} = 0.25$) which lies in the typical range for ionospheric modification experiments. Coordinates of the radio wave source were chosen as $x = y = 0$, $z = -3$ or $-4$ that corresponding the distance from the source to the beginning of the ionospheric plasma layer of $3L$, and of $4L$ from the unperturbed reflection point of the pump wave that corresponds to the reflection altitude of 150 and 200 km under typical ionospheric conditions in modification experiments ($L = 50km$). Propagation below the ionospheric plasma layer ($z < 0$) was assumed as free space propagation. All large scale irregularities were supposed to be identical in form with $a = 50$, $b = c = 5$ which corresponds to their characteristic lengths of 20 km along the magnetic field and their long horizontal axes, and of 2km along short horizontal axes. The spacing of inhomogeneities (distance between the centers of innomogeneities in the horizontal plane) was chosen to be 0.1 which corresponds to 5 km spacing for $L = 50km$. Several runs for different magnetic field inclination angles $\alpha$ and rotational angles of inhomogeneities in the horizontal plane $\psi$ were done.

## 3.3 Requirements for effective self-focusing

As was already formulated in the beginning of this section two main conditions for the pump wave self-focusing are required:

1. Propagation of the pump wave quite along the magnetic field in the upper hybrid region and large enough component of pump electric field perpendicular to the magnetic field to excite striations that can lead to the development of the depletions in mean plasma density.
2. Trapping of the pump wave by the large scale plasma density irregularities.

Both conditions were investigated in our analysis.

## 3.4 Small angles of the magnetic field to the vertical

It is rather obvious that for small angles $\alpha$ of the magnetic field to the vertical, less then approximately 20°, both conditions mentioned above can be easily satisfied: pump wave has large enough component of the electric field perpendicular to the magnetic field lines in the unperturbed ionosphere (without large scale irregularities), and any field aligned plasma density irregularity successfully traps pump wave. The simple theory developed in the section 2 is fully applicable to this case. Model calculations verify this statement. The results of calculations for inhomogeneities aligned across the magnetic meridian plane are shown in the Fig. 5 of A2. To simplify the figure, only rays corresponding to the central part of the radio wave beam cross section in the magnetic meridian plane are shown. Projection of the rays into the magnetic meridian plane is displayed in the panel A where rays trapped by different irregularities are indicated by different colours as well as non-trapped ones. Irregularities are shown by shading. It is seen, that the trapping is quite effective in this case even in the magnetic meridian plane (the worst case due to propagation effects). Therefore, one can conclude that the second condition of effective self-focusing of pump wave is satisfied for any form of the irregularities in the horizontal plane. An angle between the magnetic field and the pump wave group velocity, more accurately, the value of $\gamma' = \mathbf{b} \cdot \mathbf{v}_{gr}/v_{gr}$ (pump electric field component across the magnetic field is proportional to this value because the group velocity is proportional to the Pointing vector $\mathbf{v}_{gr} \propto [\mathbf{E} \times \mathbf{H}]$) is shown for some trapped rays (that are also marked in the panel A) in panel B. The value of $\gamma'$ for an non-trapped ray is also shown in panel B for comparison. It is easily seen that in upper hybrid region the pump wave propagates nearly along the magnetic field to efficiently excite striations, so the second condition of self-focusing is satisfied as well.

## 3.5 Low latitude ionosphere

For larger magnetic field inclinations the problem becomes much more complicated. The results of calculations for the inclination angle $\alpha = 40^\circ$ are displayed in Fig. 6–10 of A2. The case of the irregularities oriented across the magnetic meridian plane ($\psi = 90^\circ$, an angle $\psi$ is shown in the Fig. 4) is presented in Fig. 6. Again, only a part of rays corresponding to the central cross section of the pump wave beam in the magnetic meridian plane is shown. One can see from the panel A of Fig. 6 that due to the large horizontal displacement of the radio wave rays in the magnetic meridian plane—that means across the inhomogeneities in this case—irregularities cannot trap the rays, all rays just cross irregularities. The angles of rays to the magnetic field are not changed significantly by irregularities in this case as it can be seen from the panel B. We can deduce from these calculations that both conditions of self-focusing are not satisfied in this case, that means that the irregularities oriented across the magnetic meridian plane cannot be developed due to the striation mechanism of pump wave focusing considered here.

On the other hand, irregularities, oriented in the magnetic meridian plane ($\psi = 0$) can effectively trap rays, as it is shown in Fig. 7, panel A, where the central part of the incident radio wave beam perpendicular to the magnetic meridian plane is shown. Therefore, the second condition of the self-focusing is satisfied quite well. But in this case rays cannot change significantly their angle to the magnetic field—in the upper hybrid resonance region they remain close to perpendicular to the magnetic field as it can be seen from the panel B of Fig. 7, so the first condition of self-focusing (a possibility to excite striations) for this configuration of irregularities is not satisfied .

So, to trap a pump wave, irregularities should be extended enough in the magnetic meridian plane to prevent rays from simply crossing them and in the same time should take some angle with it to turn rays in the magnetic field direction to make possible excitation of striations. For magnetic field inclination of 40° to the vertical such conditions were found for the irregularities having the angle $\psi = 20^\circ$ to the magnetic meridian plane (see Fig. 4). The trajectories of the rays in the perpendicular to the magnetic meridian plane for this case are shown in panels A of Fig. 8–10 for north (Fig. 8), center (Fig. 9) and south (Fig. 10) parts of the incident radio wave beam.

Let us note that irregularities are shown by their shading, where the shading density is proportional to the density perturbations calculated along the marked rays in each irregularity (above the reflection point of the ray horizontal coordinate in the magnetic meridian plane was supposed to be equal to its value in the reflection point—that causes visual curvature of irregularities). Used this display method for irregularities seems to be most suitable, but some rays are seen as reflected rather outside the irregularities. This just indicates that orthogonal to the plane of the figure coordinates (in the magnetic meridian plane in case of Fig. 8–10) the actual ray paths substantially differ from those marked (propagation in this case is essentially three-dimensional).

It is easily seen that trapping of radio waves by density depletions is even more effective then in the case of $\psi = 0$. Evidently asymmetry in the east-west direction is connected to the direction of rotation of the irregularities, in this particular case trapping is more efficient in the west. The change of the sign of the angle $\psi$ leads to symmetry in the magnetic meridian plane pattern.

Angles of the rays to the magnetic field are shown in the panels B of Fig. 8–10. It is seen that in the south part of the beam (Fig. 10), the downward portion of the western trapped rays propagate nearly along the magnetic field. This should result in anomalous absorption due to nonlinear excitation of striations, that would in turn lead to the heating of inhomogeneities and to the self-focusing of the pump wave. Northern part of the beam (Fig. 8) also shows near-parallel propagation of some rays, but only for on very limited distances where the geometrical optics approximation used can fail. More detailed analysis of this situation is needed for unambiguous answer if there is enough electric field component perpendicular to the magnetic field in this case.

It should be also mentioned that the region of propagation along the magnetic field rays is displaced from the center of the inhomogeneity. This could lead to its motion caused by shifted heating.

So, we have demonstrated that for Arecibo, where the inclination angle of the magnetic field is large enough $\alpha \approx 40°$, there exists a real possibility for formation of large-scale nonlinear structures (*patches*) in the modified ionosphere due to self-focusing of the pump wave on the bunches of striations. On the other hand, the conditions for self-focusing are satisfied here only for special directions and not everywhere in contrast to the case of small inclination angles $\alpha$. Because of this only a part of the pump wave rays could be trapped by irregularities that explains qualitatively the main peculiarities of nonlinear structuring due to the pump wave focusing on striations in the low latitude ionosphere.

These results may reconcile the rocket and radiowave data in Arecibo modification experiments as follows. The radiowave experiment yield relatively low anomalous absorption and SEE due to the some fraction of the medium which exhibits the proper geometry. The rocket probe passed through a region which was subject to the requisite conditions.

To find optimal conditions for large scale structuring in modification experiments in Arecibo and to investigate self-consistency in solutions for ray tracing with excitation of striations a detailed further analysis is needed.

The results of this investigation prepared for publication in Radio Science in a paper "Nonlinear structuring of modified by powerful radio waves ionosphere at low latitudes". The paper is given in Appendix 2 to this report.

# 4 Conclusion

Basing on the developed during this year theory the following new effects in ionospheric modification are predicted:

1. The self-oscillations of striations in frequency range $f \geq 30 \quad 50 Hz$ with transverse dimensions less than 1 m and dimensions along magnetic field of the order 100-500 meters. Some indications on the real existence of these oscillations are shown to be seen both in VHF scattering and in the rocket observational data.

2. The new physical process – self-focusing of the pump wave on a large number of excited striations. The process results in focusing of a pump wave and formation of a bunches of striations in the scales $(0.1 \quad 1) km$. The bunches of striations and large scale inhomogenieties of these scales were observed in rocket and radio scattering experiments.

3. The process of stationary striations formation in low latitudes is shown to be deeply connected with formation of a patches of striations of kilometric scales and pump wave focusing on this structures. These results reconcile the rocket and radiowave observational data in Arecibo modification experiments.

4. A new refined analysis of the *in situ* observational data, obtained on rockets was done, what made it possible to determine the Fourier spectrum of the striations, developed in Arecibo heating experiments. This measured spectrum demonstrated a good agreement with the theory of stationary striations (Gurevich et al., 1995).

5. The future development of the work of our theoretical group would include

    1) The detailed comparison of the theory of multiple acceleration with the high height resolution experimental observations of electrons in energy range $4 \quad 16 eV$ in Arecibo using Carlson's ISR method.

    2) Development of the theory of electric field structure and its oscillations in striations. The theory would be tested against the existing rocket experimental data.

3) Development of the theory of stationary striations including selffocusing and self-oscillation processes in a high latitude ionosphere.

4) Carlson suggested that the predicted by the theory kilometric scale patches could be seen in optic emission. The detailed comparison of the theory with the existing in Carlson group experimental data are supposed to be performed.