Review of Radio-Frequency, Non-linear Effects on the Ionosphere

WILLIAM E GORDON
Rice University, Houston, Texas, USA

and

LEWIS M DUNCAN
Clemson University, South Carolina, USA

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Radio waves have inadvertantly modified the Earth's ionosphere since the Luxembourg observations of Tellegen in 1933 and perhaps since Marconi in 1901. The history of this ionosphere modification by radio waves beginning with Marconi, touching on the Luxembourg effect, its explanations and its early use to deduce the properties of the lower ionosphere in the 1930s have been outlined. The measurements became more sophisticated in the 1950s leading to the Ginzburg and Gurevich proposal in 1960 for high powered, high frequency modification experiments in the upper ionosphere. Beginning in 1970 major radio facilities were available to induce changes in the ionospheric plasma accompanied by an array of diagnostics for observing the effects. A summary of these effects up to 1986, where the natural plasma of the ionosphere is treated as a laboratory to study the physics of the medium, is presented. The work summarized was done in the USSR, the USA and Western Europe. The experimental and theoretical contributions provide a rich store of information on plasma physics. It is suggested that there is a special opportunity for east-west cooperation and collaboration.

1 Introduction

Modification of the ionosphere by high power radio waves in the megahertz band has been intensively investigated over the past two decades. This research has yielded advances in aeronomy, geophysics, and plasma physics with applications to radio communication and has provided a fruitful interaction of radio theorists and experimentalists.

There being almost no linear effects of powerful radio waves on the ionosphere, we concentrate on the non-linear effects. To put the subject in perspective we trace its history beginning in the early 1930s and highlight the important events up to the late 1960s. We then shift to a phenomenological approach and deal, in order, with ohmic heating, parametric instabilities, self-focusing and kilometre-scale irregularities, metre-scale irregularities, and a collection of recently discovered effects. We conclude with the observation that stronger international cooperation would benefit this research, and describe a list of promising, difficult challenges.

1.1 Historical Perspective

On 12 Dec. 1901 in a bold experiment that he felt would work but was not prepared to explain, Marconi transmitted the code letter S from Cornwall, England and received it in St. Johns, Newfoundland, a distance of about 3000 km around the curve of the Earth’s surface. The success of this pioneering venture, although not a non-linear ionospheric effect, started a revolution in long distance communication, ushered in an era of international science, and started the pattern of experimental observation being explained almost immediately by radio theorists. In this case it was Kennelly1 and Heaviside2 independently postulating a conducting reflecting layer aloft.

The proper beginning for radio modification of the ionosphere, however, is the report by Tellegen3 of the inadvertent modulation of the Beromünster (625 kHz) signal by the powerful signal of the Luxembourg transmitter (Fig. 1). Tellegen interestingly titled his report, “Interaction between Radio Waves?”, and within a year Bailey and Martyn4 properly ascribed the cross-modulation to ionospheric changes produced by the Luxembourg radio waves. In particular the Luxembourg wave changed the instantaneous electron collision frequency and hence the attenuation suffered by the Beromünster wave as it passed through the ionosphere near the Luxembourg transmitter, producing a modulation of the Beromünster signal patterned on the Luxembourg modulation.

In 1937 Bailey5, developing further the Luxembourg effect, suggested that if the disturbing waves were at a frequency near the gyro-frequency, the cross-modulation would be abnormally large. Some
simple experiments supported this and it was later confirmed by Cutolo. Fejer described a method using the cross-modulation techniques to obtain electron density and collision frequency profiles (Fig. 2) in the D region under certain assumptions. The technique compares the amplitude of a disturbed and an undisturbed train of wanted waves while altering the interaction height through changes in the relative time of wanted pulses and the disturbing pulses.

A powerful radio wave in the ionosphere not only is capable of applying its modulation to other signals passing through the same plasma but also is distorting itself in ways that have been described as self-demodulation and non-linear distortion.

1.2 Active Experiments

As the phenomena of cross-modulation and wave self-interaction became better understood, a number of researchers began to recognize the potential of using high-power radio waves to modify the ionosphere in controlled experiments. In a direct extrapolation of the developing cross-modulation theory, Bailey and Goldstein suggested using radio waves near the electron gyro-frequency to control ionospheric electron temperatures, thereby affecting temperature-dependent ionospheric processes such as diffusion, attachment, and recombination. They also suggested the complementary nature of controlled ionospheric experiments and laboratory plasma studies.

High-power radio wave modification of the F-region ionosphere was proposed by Ginzburg and Gurevich. Specific heating effects were investigated by Farley and Gurevich, estimating the expected increases in F-region electron temperatures and associated density redistribution resulting from plasma diffusion along the geomagnetic field lines. Bailey also suggested using powerful radio waves to generate artificial airglow in the nocturnal E-region. Ginzburg and Lombardini investigated in detail the possibility of artificially ionizing the lower ionosphere by acceleration of electrons in the electric field of high-power radio waves, concluding that impractically high radiation power densities were necessary.

A collection of ionospheric modification techniques, known somewhat imprecisely as "ionospheric heating", began to emerge from the cross-modulation and wave interaction studies. An early attempt to detect ionospheric heating effects with a relatively weak 7.7 MHz system was unsuccessful. In an experiment investigating ionospheric absorption and associated recovery time constants, Klemperer used the 50-MHz Jicamarca Radio Observatory facility to modulate the measured cosmic radio noise intensity. And using Arecibo incoherent scatter radar measurements to infer changes in the electron temperature, Showen investigated changes in the ionosphere under the influence of a
high-power 40-MHz radio wave. These early experiments demonstrated that controlled ionospheric modification experiments were possible using suitably powerful facilities. Modern radio transmitters were being constructed capable of generating these powerful radio waves, leading to the development of several dedicated ground-based ionospheric modification facilities in the late sixties and early seventies\(^2\). More recently, new modification facilities have been operated at Arecibo, Puerto Rico and Tromsö, Norway.

2 Heating

The original ionospheric modification experiments using high power HF radio waves were intended to produce small perturbations in the local thermal balance as a tool to study heating and cooling processes, collision rates, and scattering cross-sections. The ionospheric D, E and F regions have been disturbed and then allowed to relax to ambient conditions yielding heating and cooling time constants and electron density variations\(^2\). As the electrons are heated in the lower ionosphere, the collision rate increases and hence the radio wave absorption. Shlyuger\(^2\) reported the temperature rises by a factor of 20 (a daytime observation) to 40 (a nighttime observation) at a height of 70 to 80 km and the electron collision frequency increases by a factor of eight. The absorption of a radio wave passing through this region is increased by 25 to 30 dB. At even higher powers an increase in the intensity of the wave suggests a saturation effect.

Cohen and Whitehead\(^2\) reported a drop in signal strength of 10 dB for a wave reflected at the height of the disturbed F region. A similar result is reported by Utalut and Violette\(^2\) (Fig. 3). Stubbe et al.\(^2\) reported that the intensity of wave reflected in the disturbed F region drops by up to 15 dB when the disturbing wave transmitter is turned on. Varying the transmitter power of the disturbing wave produced no change in the reflected wave field strength when the ionosphere was "quiet", but the attenuation decreased when the disturbing wave power was decreased and the ionosphere was variable, lending credence to a comment by Das and Fejer\(^2\) calling for a low level of variability in the undisturbed ionosphere if striations are to develop when the ionosphere is disturbed.

3 Parametric Instabilities

One of the more remarkable discoveries of the early HF ionospheric modification experiments was the detection of a rich spectrum of plasma instabilities excited near the HF reflection height. These non-linear wave-plasma interactions can be collectively described as parametric instabilities, characterized by a pump or driving field whose energy cascades into plasma oscillations at two lower natural resonant frequencies in the plasma. In the present ionospheric modification experiments, the high power HF electromagnetic radiation provides the initial driving field and the longitudinal electrostatic electron plasma wave and the ion-acoustic wave (parametric decay instability) or zero-frequency ion mode (purely growing instability) represent the parametrically enhanced oscillations. In addition, direct linear mode conversion and stimulated Raman scatter can produce enhanced plasma oscillations at the pump frequency, while stimulated Brillouin scatter may also generate enhanced ion-acoustic fluctuations.

The non-dissipative parametric instability is driven by the so-called ponderomotive or striction force\(^3\). The possibility of excitation of such instabilities in the ionosphere was first suggested by Perkins and Kaw\(^3\). Refinements of this non-linear wave-plasma interaction theory, as applied specifically to high-power ionospheric modification experiments, were contributed by Dubois and Goldman\(^3\) and Fejer and Leer\(^3\). The experimental excitation of plasma waves in the ionosphere was first
observed by Carlson et al.\textsuperscript{35} (Fig. 4) and reported by Wong and Taylor\textsuperscript{36}.

The resulting enhanced electrostatic turbulence is easily detected and studied using incoherent scatter radars. Echoes enhanced by up to several orders of magnitude are routinely observed at both the ion-acoustic and electron plasma wave frequencies, at an altitude just below the HF reflection height. These parametric instabilities are excited only for ordinary polarization of the incident pump radiation; extraordinary polarized waves do not reach the proper altitude for generation of these phenomena.

An example of typical radar returns for parametrically enhanced plasma waves is presented in Fig. 5. A study of the height of excitation of these enhancements\textsuperscript{37} indicated that the observed parametric instability is generated near the first maximum of the Airy interference region below the reflection altitude. Radar measurements of the spectra of these enhanced plasma waves (Fig. 6) (Refs 38-40) described the enhanced plasma wave structure, including additional features apparently associated with the saturation of the parametrically enhanced oscillations. These spectral structures have been explained in terms of a saturation mechanism based on secondary parametric decay interactions, with the enhanced electrostatic plasma oscillations acting as new pump waves\textsuperscript{41-43}. The effect of plasma wave propagation on the observed structures has been brought out by Arnush \textit{et al.}\textsuperscript{44} and Muldrew\textsuperscript{45}.

Each of the enhanced waves is affected by both Landau and collisional damping. The Landau damping, or some associated electron acceleration process, gives rise to extrathermal electrons\textsuperscript{46-48}. Through impact excitation of atomic oxygen, these energetic electrons are believed to be responsible for the observed enhancements in 6300 Å and 5577 Å airglow emission lines associated with HF heating\textsuperscript{49}. Enhanced plasma waves have also been excited and observed in sporadic-E layers\textsuperscript{50}.

Studies of the enhanced plasma line rise and decay time behaviour have been conducted in a series of pulsed HF observations\textsuperscript{51,52}. Djuth\textsuperscript{52} also reports the discovery of a plasma line ringing phenomenon presented in Fig. 7. Following HF turn-on the plasma line intensity is seen to oscillate with a period of about 2 s for a very long time. This effect is surprisingly most pronounced for low incident HF pow-
ers. Other studies of temporal fluctuations in the steady-state plasma line intensity have been conducted, but these longer period variations are more usually interpreted in terms of large-scale spatial structures drifting.

The initial observations of plasma lines at Eiscat by Hagfors et al.\textsuperscript{53} show the structural features of the spectrum observed at Arecibo but have the novel and surprising feature of a pronounced overshoot (20 dB or more) followed by a virtual disappearance of the enhanced fluctuations after a few hundred milliseconds. Overshoot at Arecibo are normally less pronounced but leave a substantial plasma line behind. There are obvious experimental differences in magnetic dip angle and diagnostic radar frequency between Arecibo (45°, 430 MHz) and Eiscat (77°, 933 MHz) but the explanation of the differences in the observations is yet to be proposed.

The strong overshoot followed by disappearance of the plasma line is illustrated in Fig. 8. The power in the plasma line rises very rapidly with heater turn on but decays with a time constant of about 130 ms while the heater remains on for 0.4 s in (a) and 2 or 4 s in (b). The characteristic spectral lines are illustrated and labelled in Fig. 9. A comparison of Fig. 9 with Fig. 6 shows the similarities and the merging of the cascade modes at Arecibo rather than the separation as at Eiscat.

Frey et al.\textsuperscript{54} observed scintillations of radio stars over Tromso associated with electron density irregularities produced by the HF heater. HF power densities of 20-40 \( \mu \)W/m\(^2\) incident on the overdense ionosphere exceeded the threshold for large scale (150-450 m) electron density irregularities. Scintillations had been observed at Arecibo by Frey under similar experimental conditions with quite different geomagnetic geometry. The radio star scintillations of Frey et al.\textsuperscript{54} and the HF fading observed by Jones et al.\textsuperscript{55} are evidence of self-focusing by the heater.

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Fig. 7—Observations of the plasma-line ringing phenomena\textsuperscript{52}

Fig. 8—Observations of enhanced plasma lines at Eiscat during heating experiments\textsuperscript{53}
Incoherent scatter radar studies of HF induced large-scale ionospheric irregularities rely on measurements of the parametrically enhanced plasma waves discussed in Section 3. The amplitude of the enhanced plasma waves directly depends on the local power of the pump electric field. In addition, because these enhanced waves are detected at only one altitude, systematic scanning of the narrow radar beam across the HF interaction region can yield a cross-sectional map of the local electric field intensity. These two-dimensional maps of plasma line intensity clearly show focusing of the incident HF radiation and large-scale structuring of the illuminated plasma. As the radar beam remains fixed, ionospheric winds drift the large-scale structures through the beam. Combinations of fixed and scanning radar measurements, as shown in Fig. 10, have been used to determine typical striation scale sizes of 0.5-1.5 km, as well as to monitor the background drift velocities.

Satellite-borne ion density probes on Atmospheric Explorer have been flown through the HF interaction volume, directly measuring striation scale sizes from several kilometres to as small as 60 m, limited by the telemetry rate on that information channel. The measured structures are located within the HF interaction region with typical associated density fluctuations of about 1%.

4 Self-focusing and Large-scale Irregularities

Large-scale (kilometre-size) field-aligned ionospheric density irregularities are commonly generated during HF ionospheric modification experiments. These large-scale structures are believed to be responsible for the artificial spread-F detected by Utzau et al. and further investigated by several workers. More recent investigations have used incoherent scatter radar observations, AE satellite measurements, and both satellite and radio star scintillation studies. These large-scale irregularities are believed to be produced through thermal self-focusing of the incident HF radiation.

Fig. 9—Observations of enhanced plasma line spectrum at Eiscat during heating experiments.

Fig. 10—Observations of the enhanced plasma line signal strength in relative power using both fixed and scanning radar measurements, showing the beam self-focusing effects.
Scintillation studies of the HF induced irregularities have been conducted using signals from both satellites and radio stars. Strong scintillations at VHF and UHF have been associated with the generation of these irregularities, as shown in Fig. 11. The striations have been observed to develop on time scales of 20-30 s but to decay with much slower time constants. Again the associated electron density perturbations have been estimated to be of the order of 1%. Scintillation studies in the microwave frequency regime have thus far been inconclusive, hindered by instrumental uncertainties.

The influence of beam focusing and large-scale ionospheric irregularities, both natural and HF amplified, on the parametric instability process has been addressed by Muldrew. The role of these ionospheric ducts in determining the altitude of parametric excitation and associated enhanced plasma line amplitudes appears to be a very important consideration. In particular, HF ducting may help to explain the difference in observation height between natural photoelectron enhanced plasma waves and the HF enhanced waves for the same observing frequency, and the unusually high signal amplitudes detected for the Arecibo radar observational geometry.

5 Short-scale Structures

One of the unexpected effects of the early HF ionospheric modification experiments was the generation of intense short-scale (metre-size) field-aligned density striations. A number of theoretical models have since been proposed to explain their development. Despite a great deal of experimental information on these aspect-sensitive short-scale striations, the responsible excitation mechanism has not yet been resolved.

Experimental studies of short-scale striations have involved the measurement of HF, VHF and UHF coherent radar backscatter from the E- and F-region HF interaction volume. These echoes are highly aspect sensitive, indicating that the scattering structures are closely aligned to the magnetic field. Recent studies have concentrated on measurements of the striation growth and decay time constants, drift velocity, and dependence on incident HF wave power and polarization (Fig. 12). Growth and decay time constants have been measured to be of the order of 10 ms. The short-scale striations, similar to the parametrically enhanced plasma waves, develop only for z-mode HF polarization and only when the pump frequency is less than the ionospheric critical frequency. A strong correlation exists between the incident pump power and the short-scale striation scatter, as shown in Fig. 13.

Belenov et al. working with scattering from striations having cross-sections of 12 to 25 m find time constants of the order of 10 s using disturbing transmitter cycles of 7 min on and 8 min off and time constants of seconds when the disturbing transmitter is cycled 1 min on, 1 min off suggesting an "accur-
mulation” effect. Coster\textsuperscript{83} reports E- and F-region time constants of milliseconds and seconds, respectively, for scattering from 3 m diameter striations when the ionosphere is “pre-conditioned” (i.e. accumulation effect operating). Coster calculates that the observed time constants do not agree by one or more orders of magnitude with the values predicted by Grach \textit{et al.}\textsuperscript{84} or by Das and Fejer\textsuperscript{85} for an inhomogeneous medium (horizontally stratified ionosphere).

The striation drift velocity has been found to be independent of the HF radiated power, but well correlated with the general F-region ionization drift\textsuperscript{86}. A comparison of short-scale striation and large-scale irregularity drift velocities during a period of simultaneous observations, presented in Fig. 14, shows reasonably good agreement between the two measurements.

6 Ionospheric Cavities

Recent Arecibo HF studies have detected soliton-like structures excited in the F-region ionosphere over a wide range of spatial and temporal scale sizes. These observations represent a significant step in relating current theoretical, computer simulation, and laboratory plasma results with the ionospheric modification experiments. Furthermore, the extended scope of these controlled modifications offers the opportunity for many additional aeronomy and geophysics research applications.

Computer simulations of high-power HF radiation incident on an ionospheric plasma critical layer predict the initial formation and collapse of small-scale solitons in the vicinity of HF reflection\textsuperscript{86}. Recent observations by Birkmeir and Hagfors\textsuperscript{87}, using a new chirped radar technique, argue strongly for the formation of such structures within a few kilometres of the unperturbed HF reflection height. These results measure density variations of a few per cent $\Delta n/n$ and generation times of less than one second.

Soliton formation and evolution has also been proposed as an explanation for rapid excitation height changes associated with distinct features of the plasma line overshoot\textsuperscript{88}. A height rise of several hundred metres and subsequent excitation region broadening occurs in approximately 20-50 ms after HF turn-on, accompanying the main plasma line overshoot effect, as shown in Fig. 15. This rapid rise

![Graph of Ionospheric Cavities](image-url)
is in good agreement with the previously described chirped radar results, and also indicates a ponderomotively driven non-linear profile modification process.

Arecibo experiments have also detected the development of HF-induced large-scale ionospheric thermal cavities. These structures show density depletions as large as 75% \( \Delta n/n \), cross-field scale sizes of several kilometres to tens of kilometres, extensions along the geomagnetic field by hundreds of kilometres, and strong trapping of the incident HF and parametrically pumped electrostatic radiation. Fig. 16(a) shows results of a computer simulation of electromagnetic waves incident on a critical plasma surface. Even though this model utilized calculations appropriate for a laboratory plasma environment and ponderomotive driving force, the underlying physical process is apparently equally applicable to ionospheric thermal effects, as evidenced by the close resemblance of the corresponding ionospheric thermal cavities presented in Fig. 16(b). In addition, the cavity structural development exhibits several other soliton-like characteristics, including nucleation, bifurcation and burn-out processes, the ability to propagate through neighbouring cavities while maintaining discrete structural identities, and sharp profile steepening of the upper plasma boundary. Thermal cavity formation occurs on a time scale of several minutes and decay follows on a time scale exceeding 30 min. This profile recovery process also occasionally shows gradient-drift-like turbulence on striation edges. These large-scale thermal cavities have been detected only during late night Arecibo observations. The specific HF and ionospheric conditions necessary for their excitation are still under study.

7 Additional Non-linear Effects

The basic physics of high-power HF interactions with the ionosphere has advanced to a sufficient level of understanding that experimenters are now beginning to investigate controlled secondary non-linear effects. These are generally excited using a frequency or amplitude modulated HF pump wave, or by multiple pump ionospheric heating. An example of this kind of non-linear effect studied recently is the control of parametric instabilities through pump modulation and parametric interactions and double resonance excitation by multiple pump ionospheric heating.

Sinusoidal variation of the HF pump center frequency has been used to suppress the excitation of parametric instabilities, as shown in Fig. 17. This non-linear effect can be explained in simple terms. Since at any altitude the parametric interaction process requires very specific frequency and wave number matching conditions, rapid variation of the pump center frequency can be used to assure that the instability conditions are never satisfied at any altitude for times approaching the instability growth rate time constant. Considering the frequency modulation as a distribution of the incident power.
among a number of discrete sidebands, the appropriate modulation can be chosen so as to keep the power in each discrete pump frequency sideband below the instability threshold.

This argument is no longer valid when the separation frequency of the multiple pumps approaches a resonant frequency of the plasma. When multiple HF pumps were used with separation frequencies which were multiples of the ion-acoustic frequency, plasma wave enhancements stronger than the single-frequency pump excitation levels were measured. The beat wave of two HF pumps is believed to directly drive the ions, lowering the instability threshold and producing the strong plasma wave enhancements. These multiple pump results can be explained as the result of coherent parametric instabilities\(^9\) or double resonance excitation\(^9\).

Another non-linear effect attracting a great deal of attention recently is the generation of waves at the combination frequency, and multiples of two high-power pump waves. This so-called non-linear detection effect was first discussed by Ginzburg\(^6\) and Vilenskii\(^9\). Observations of the detection effect were first reported by Getmantsev et al.\(^7\), followed by detailed theoretical analyses\(^8\). The generation of low-frequency electromagnetic radiation through controlled HF pulsing was also described by Ferraro et al.\(^9\). Strong enhancements of the detection effect resulting from HF-induced modulation of the polar ionospheric currents has been reported by Stubbe et al.\(^28\). Studies of these non-linear wave interactions continue in current HF ionospheric modification experiments.

Modulation, at a few kilohertz, of the HF pump frequency produces a detectable signal at the modulation frequency at distances up to 6000 km. Lunnen et al.\(^10\) observe signals near 2 kHz that they attribute to the radiation from a modulated ionospheric current near 70 km altitude over powerful transmitters at Tromso, Arecibo, and Jicamarca. The radiation is injected into an earth-ionosphere cavity and received on a tuned loop antenna. The paths include Tromso to Pennsylvania State University (PSU) (6078 km), Arecibo to PSU (2700 km), Jicamarca to Puerto Rico (3532 km), and Arecibo to various sites (a few km to a few hundred km). The pump frequencies are near 3 and 5 MHz except at Jicamarca where the pump is near 50 MHz. The signals are detectable but require several minutes of averaging. The ionospheric currents include the equatorial electrojet over Jicamarca (near Lima, Peru), the polar electrojet over Tromso, Norway, and a mid-latitude current over Puerto Rico. Results obtained by Ferraro et al.\(^9\) indicate a phase height of the ELF generation near 70 km.

8 Conclusion

In preparing this paper we find a relative imbalance in the emphasis of the scientists of the USSR and the USA. Judging by the published material, it appears that our colleagues in the USSR are most recognized for their theoretical developments, whereas our colleagues in the USA emphasized experimental work. This is not to imply any shortcoming on either side, for the eastern literature and the western literature on ionospheric modification have a rich store of theoretical ideas and observational data. The apparent imbalance serves as the basis for our earlier observation that stronger cooperation would benefit this research.

Among the problems we recognize looking ahead are the following: (i) The plasma line observations at Eiscat defy present theory and the extension of observational evidence from lower latitudes. (ii) The natural plasma laboratory of the ionosphere is only loosely coupled with laboratory plasma physics. (iii) The opportunity to perform experiments in the upper atmosphere as well as observe the natural variations has yet to be fully exploited in aeronomy and geophysics. (iv) The application of artificially induced striations to long distance communications needs to be better understood and demonstrated.

Historically in the study of ionospheric physics, theory has been relatively poor at predicting experimental results, although quick to explain observations once they have been made. The complex, interactive nature of the non-linear radio-frequency phenomena in the ionosphere require a coordinated, complementary programme of both experimental and theoretical studies so as to meet the future challenges of ionospheric modification research.

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