IN-SITU MEASUREMENTS TO UNDERSTAND SOLAR BURSTS

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The S/WAVES experiment on STEREO has several proposed new features designed to understand the medium and the mechanisms of solar radio burst generation.

The major part of S/WAVES, not discussed here, is devoted to remote tracking of type II and type III bursts, in order to investigate the structure of the inner heliosphere and to track Coronal Mass Ejections and other phenomena.

The present work describes only a small part of the S/WAVES experiment for STEREO. This part is aimed at understanding the generation mechanism of radio bursts, by concentrating on the Langmuir waves which are their progenitors.

Among these new features are proposed:

A slow rate science system to measure density fluctuations and fields in order to identify the wave modes responsible for the density ramps.

Use of the monopole and dipole antennas in combination to measure density fluctuations.

There will be an improved Time Domain Sampler system, improved over that of Wind-Waves in precision, linearity and sample length and rate.

A "histogram" system to collect statistics on Langmuir wave amplitudes, among other things for a test of the Stochastic Growth Theory and to provide data for a calculation of various electromagnetic wave generation processes. Previous systems have only given information on averages or on the most intense Langmuir waves.

A loop antenna to distinguish the magnetic component of Langmuir mode waves which have become Z-mode waves on a density ramp.

DENSITY FLUCTUATIONS AND RADIO BURSTS

We believe that density fluctuations play a fundamental role in the conversion of Langmuir waves to electromagnetic waves (Field, 1956; Kellogg, 1986; Hinkel-Lipsker et al, 1992; Yin et al, 1998, Yin and Ashour-Abdalla,1999; and Willes and Cairns, 2000). An important consideration is that the Langmuir waves generated by typical solar wind electron beams are so close to the plasma frequency that known variations in the plasma frequency are larger than the Langmuir wave-plasma frequency difference. Hence the Langmuir waves may quickly reach a place where they are reflected, with mode conversion to electromagnetic waves in some cases, and with temporary conversion to Z mode if the incidence of the wave on the density gradient is oblique.

As an illustration of the importance of density fluctuations in the generation of Langmuir waves and their conversion to electromagnetic radiation, we show in Fig. 1 a reconstructed time series of plasma frequency, obtained by inverting a published density spectrum (Celnikier et al, 1987, Fig. 8)...The curve shows the fluctuations in plasma frequency, and the bars show the difference between the plasma frequency and the frequency of Langmuir waves resonant with two different beam energies. It will be seen that the fluctuations in plasma frequency are large compared to the Langmuir wave frequency difference, meaning that the Langmuir waves will quickly be reflected at density enhancements. It will also be seen that density fluctuations in the 1 Hz range are important.

The spectrum of density fluctuations in the relevant frequency range has hardly been measured, and in any case, existing measurements refer to averages over a fairly long time interval, and have not been made in the generation region of a radio burst.

If the Langmuir wave is incident obliquely on the density gradient, which will be the case nearly universally, then the wave develops an appreciable magnetic component in the course of being reflected. A loop antenna is proposed to measure this magnetic component, and WKB approximation calculations of the magnetic component during the reflection are shown in the section on this loop.

The measurement of density together with the magnetic field measurements of STEREO-IMPACT will facilitate identification of the modes of fluctuations in the solar wind.

Density fluctuations in the range of 1 Hz are also of importance in the scattering of radio waves from distant sources, the InterPlanetary Scintillation measurements, from which much of our knowledge of the acceleration of the solar wind near the sun is obtained. In these measurements, it is assumed that the fluctuations are at relative rest in the plasma, and identification of the modes of what fluctuations remain at 1 AU will help to strengthen this assumption.

PRINCIPLE OF THE DENSITY MEASUREMENT

Although the best way to measure rapid fluctuations in density would be with a large aperture retarding potential analyzer (Kellogg et al., 1999a), this was rejected as part of the experiment complement of S/WAVES. Instead, we will try the following method.

Pedersen, 1995; Escoubet et al., 1997, and Scudder et al., 2000, have shown that spacecraft potential relative to the plasma can be used to measure plasma density in the magnetosphere. Spacecraft potential is determined by a combination of density and ambient electron flux rather than density alone, but density is the largest determinant of flux. In any case, measurement of spacecraft potential requires a probe which can be biased to be near the plasma potential, which is done by balancing the relatively constant photoemission current with a known constant current from the spacecraft. We have not been able to implement this system in our proposed S/WAVES experiment. Instead we propose to measure the potential difference between the S/WAVES antennas, made of Be-Cu, and the spacecraft body, mostly covered with Indium Tin Oxide. These two materials seem to have different photoemission efficiencies and different photoelectron temperatures.

The following is an oversimplified model of the effect to be measured. The potential of an isolated body in the solar wind is determined by a balance between photoemission and pickup of ambient electrons. Very roughly, the photoemission current is given by:

$$I_{\square} = e\, A_{\square}\, J_{\square} \exp(-eV/kT_{\square})$$

where $T_{\square}$ is the photoelectron temperature, $J_{\square}$ is the photoemission per unit area, $A_{\square}$ is the area exposed to sunlight and V is the body potential relative to the plasma. The electron pickup current is

$$I_p = e\, A_p\, J_p\, (1 + g)$$

where A_p is the area for electron pickup, usually the total conducting area, and J_p is

$$J_p = n \sqrt{kT_p / 2\square\, m}$$

Here T_p is the electron temperature, n is the electron density and m is the electron mass. g is a factor depending on the shape of the body and its potential relative to the electron temperature, and which is small when the body potential is small compared to the electron temperature, and which we take to be zero in this present simple theory. However, for a long cylindrical body, g is proportional to eV/kT_p and so I_p is accurately proportional to density when eV/kT_p is large.

These currents must balance for an isolated body, giving:

$$V = (kT_{\square}/e) \ln (A_{\square}\, J_{\square} / A_p\, J_p)$$

For small changes in J_p, the potential difference between two bodies with different photoemission properties then is

$$\square\square V = (kT_{\square 1} - kT_{\square 2}) /e \ (\square J_p / J_p)$$

In this way, fluctuations in flux can be tracked. In a more realistic case, the current-voltage characteristic of a body in sunlight is more complicated, so that the effective photoelectron temperature varies with the body potential (Scudder et al., 2000). The measurement will have to be calibrated, using averaged flux measurements from the plasma instrument.

We have tried this calibration on Wind-Waves. The Waves experiment on Wind (Bougeret et al., 1995) measured the potential difference between three of its Be-Cu monopoles and the spacecraft body, also covered with Indium Tin Oxide. In Fig. 2 are plotted the measured potentials for the three monopoles vs flux obtained from the 3DP experiment on Wind (Lin et al 1995). Of these, the pentagons are for the Z antenna, a Be-Cu antenna of 2.8 cm dia and oriented perpendicular to the solar direction; the squares are for the X antenna, of Be-Cu wire .38 mm dia and 50 m long, oriented at 45 deg to the sun for these measurements; and the triangles are for the Y antenna, 7.5 m long, otherwise as the X antenna. Clearly, the potential difference can be used, in the case of the X and Z antennas, to measure flux. The principle cannot be used for rapid measurements of density on Wind, as Wind is a rotating spacecraft, and also the quantization of the potential difference measurement is too coarse. But it seems that it will work on a three-axis stabilized spacecraft, except possibly for large fluxes.

TIME DOMAIN SAMPLER

The Time Domain Sampler (TDS) samples waveforms at a rapid rate and saves selected waveform "events" for telemetering to ground. The TDS for STEREO S/WAVES will be modeled after, but improved over, the TDS for Wind-Waves. Among the improvements are:

The S/WAVES TDS will sample at 250 ksps compared to 120 ksps for Wind-Waves. This is the sample rate intended for the observation of the Langmuir waves which are associated with the generation of type II and III solar radio bursts. Lower sample rates can also be commanded. On rare occasions the plasma frequency exceeded the 60 kHz Nyquist frequency of Wind-Waves, but a more important reason is to extend the range over which harmonics of the plasma frequency can be measured and to accurately measure waveforms which have been distorted by nonlinear effects. It is well known (Kellogg et al., 1976; Boswell and Kellogg,1983; Llobet et al., 1985, Kellogg 1992) that electron beams generate harmonics of the plasma frequency. A tantalizing example seen by Wind-Waves is shown in Fig. 3, but we are not confident that the harmonics are not due to nonlinearity of the A/D converter.

The S/WAVES TDS will use a linear A/D converter with 16 bits rather than the quasi-logarithmic 8 bit converter used in Wind-Waves. Harmonics of the fundamental plasma frequency were frequently observed with Wind-Waves, but the linearity of the

Wind-Waves converter was sufficiently uncertain that observations of harmonics of the plasma frequency were considered to be unreliable.

The quasi-logarithmic converter of Wind-Waves also raised the threshold for observation of a weak signal in the presence of a strong one. The low frequency waves which might be the product of two-wave decay of Langmuir waves are just such weak signals, and their observation is important for understanding the evolution of Langmuir waves.

The length (in time) of the waveform "events" will be doubled relative to Wind-Waves, to 33 msec. Langmuir waves observed by Wind-Waves sometimes obviously extended beyond the 17 msec observation interval.

THE LANGMUIR WAVE HISTOGRAM SYSTEM

Calculation of electromagnetic wave power by various conversion processes depends, not just on the Langmuir wave amplitude, which is the usual measurement, but on the square (classic theory of fundamental), and on the fourth power (classic theory of harmonic) of the amplitude. This cannot be accurately estimated either from averaged measurements of the wave amplitude, or from selected large bursts (Kellogg et al., 1999b). What is needed to distinguish between various theories is more detailed statistics of wave amplitudes. It is proposed to collect such statistics, by sampling the waveform amplitude, either maximum or average amplitude in a short time interval (several msec), and to record the number of times that such an amplitude has occurred in a period of several minutes to an hour. This histogram of wave intensity will be telemetered periodically. From this information, the electromagnetic wave power can be calculated according to various theories and compared with observation.

LOOP ANTENNA

We have proposed to add a loop antenna to the sensor complement. This antenna would be a single loop, measuring one component of the RF magnetic field. Its purpose is to measure the relatively strong magnetic component which develops when a Langmuir wave encounters an increase in density and becomes a Z mode wave. (Kraus-Varban 1989, Bale et al. 1998) This process takes place when the Langmuir wave is obliquely incident on the density gradient.

The process is illustrated in Fig. 4 for a Langmuir wave which is incident at an angle of 11 deg. to a density gradient. The top panel shows the dispersion relation for the three modes of plasma, the Langmuir wave, which remains near the plasma frequency for large k, and the two electromagnetic modes. We suppose that the Langmuir wave has been generated by an electron beam of a few keV, so that the resonant k value lies near the right side of the figure. As the wave propagates into an increasing density, its frequency remains relatively constant, since the time variations of the plasma density are very slow, and so k must decrease, and the wave moves to the left.

The third panel down shows the development of the magnetic component, as calculated using the WKB approximation and a warm plasma code. The curve is slightly irregular near $kc/\square_p = .1$ because of roundoff error in the warm plasma code. Willes and Cairns (2000) have given better calculations. The curve shows that cB becomes about

.01 of the electric field of the original Langmuir wave. For a typical Langmuir wave amplitude of 10 mV/m, this gives B equal to 3 10^{-4} nT, which is easily measurable, as is seen in Fig. 5 which shows the sensitivity achievable for a 6 inch dia. loop, and available preamplifier devices .

To measure the magnetic component of electromagnetic radiation is more difficult. A typical type III burst of flux 10^{-16} W/m^2-Hz has a field strength of only 7 10^{-7} nT, so that only extremely strong bursts might be measurable.

CONCLUSIONS

The present work has described, of course, only a small part of the S/WAVES experiment for STEREO. This part is aimed at understanding the generation mechanism of radio bursts, by concentrating on the Langmuir waves which are their progenitors.

Although a basic theory of the conversion of Langmuir waves to electromagnetic radiation, at both the fundamental and harmonic of the plasma frequency, have existed for decades, these theories have not generally taken into account the large fluctuations in plasma density which are present in the solar wind. More recent theories have tried to take these fluctuations into account, and have shown that they are of fundamental importance. (Kellogg, 1986; Melrose et al., 1986; Robinson, 1993; Yin et al., 1998; Yin and Ashour-Abdalla, 1999).

The present work attempts, for the first time of which we are aware, to make simultaneous measurements on a time scale relevant to the conversion of Langmuir waves to electromagnetic radiation, of electron density and of Langmuir waves, as well as plasma frequency magnetic fields which are expected to be indicative of the conversion process.

Bale,.S.D., P.J.Kellogg,K.Goetz,S.J.Monson, "Transverse Z-Mode waves in the terrestrial electron foreshock", Geophys.Res.Lett 25, 9, (1998)

Bougeret,J.-L., M.L.Kaiser, P.J.Kellogg, R.Manning, K.Goetz, S.J.Monson, N.Monge, L.Friel, C.A.Meetre, C.Perche, L.Sitruk and S.Hoang, "WAVES: The radio and plasma wave investigation on the Wind spacecraft", Space.Sci.Rev. 71, 231, (1995)

Boswell, R.W. and P.J.Kellogg, “Characteristics of Two Types of Beam Plasma Discharge in a Laboratory Experiment” Geophys.Res.Lett 10,565-68, (1983)

Celnikier,L.M., C.C.Harvey, R.Jegou, M.Kemp, and P.Moricet, “A Determination of the Electron Density Fluctuation Spectrum in the Solar Wind, using the ISEE Propagation Experiment” Astron.Astrophys. 126,293-298,(1983)

Celnikier,L.M., L.Muschietti and M.V.Goldman, “Aspects of Interplanetary Plasma Turbulenc”, Astron. and Astroph. 181, 138-154, (1987) Escoubet, C.P., A.Pedersen, R.Schmidt and P.A.Lundquist, "Density in the magnetosphere inferred from ISEE 1 spacecraft potential", J.Geophys.Res 102, 17595, (1997)

Field, G.B., “Radiation by Plasma Oscillations”, Ap.J. 124, 555-70, (1956)

Hinkel-Lipsker,D.E.,B.D.Fried and G.J.Morales, "Analystic expressions for mode conversion in a plasma with a linear density profile" Phys.Fluids B, 4, 559, (1992)

Kellogg,P.J., D.G.Cartwright, R.A.Hendrickson, S.J.Monson and J.R.Winckler 'The University of Minnesota Electron Echo Experiments' Space Research XVI, Akademie-Verlag, Berlin (1976)

Kellogg, P.J. and R.W.Boswell 'Beam-Plasma Instabilities and the Beam Plasma Discharge' Phys. Fluids 29, 1669-74,(1986)

Kellogg, P.J. 'Observations concerning the generation and propagation of Type III Solar Bursts', Astron. and Astrophys. 169, 329-335, 1986

Kellogg,P.J., 'Electron Beams and their Interactions with the Ionosphere-A Review of the E//B Series', Adv.Space.Res.12,(12)15 to (12)28, 1992

Kellogg,P.J.,K.Goetz,S.J.Monson and J..R,Wygant, "A Density and Current Plasma Wave Antenna", J.Geophys.Res. 104, 12627, 1999

Kellogg,P.J.,K.Goetz,S.J.Monson and S.D.Bale, "Langmuir Waves in a Fluctuating Solar Wind", J.Geophys.Res. 104, 17069, 1999

Kraus-Varban,D., "Beam instability of the Z mode in the solar wind" J.Geophys.Res.94,3527, (1989)

Lin,R.P, et al, ‘A Three Dimensional Plasma and Energetic Particle Investigation for the Wind Spacecraft’ Space Sci.Rev. 71, 125, (1995)

Llobet,X., W. Bernstein and A. Konradi, 'The Spatial Evolution of Energetic Electrons and Plasma Waves During the Steady State Beam Plasma Discharge', J. Geophys.Res. 90, 5187-96, (1985)

Melrose, D.B., G.A.Dulk and I.H.Cairns, "Clumpy Langmuir waves in tpe III solar radio bursts", Astron and Astrophys. 163, 209-238, (1986)

Pedersen,A., "Solar wind and magnetosphere Plasma diagnostics by Spacecraft Electrostatic Potential Measurements", Ann. Geophysicae 13, 188-129, (1995)

Robinson, P.A. "Stochastic-Growth Theory of Langmuir Growth-Rate Fluctuations in Type III Solar Radio Bursts", Solar Physics 146, 357-363, (1993) Scudder, J.D.,X.Cao and F.S.Mozer, "The Photoemission Current -Spacecraft Voltage Relation: Key to Routine, Quantitative Low Energy Plasma Measurements" J.Geophys.Res. (2000)

Willes, A.J. and I.H.Cairns, "Generalize Langmuir Waves in magnetized kinetic plasmas" Physics of Plasmas 7 3167-8-, (2000)

Yin,L., M.Ashour-Abdalla, M.El-Alaoui, J.M.Bosquet and J.-L.Bougeret, "Generation of electromagnetic fpe and 2 fpe waves in the Earth's electron foreshock via linear mode conversion" Geophys.Res.Lett.25, 2609-12, (1998)

Yin,L. and M.Ashour-Abdalla, "Mode Conversion in a Weakly Magnetized Plasma with a longitudinal density profile", Physics of Plasmas, 6, 449, 1999

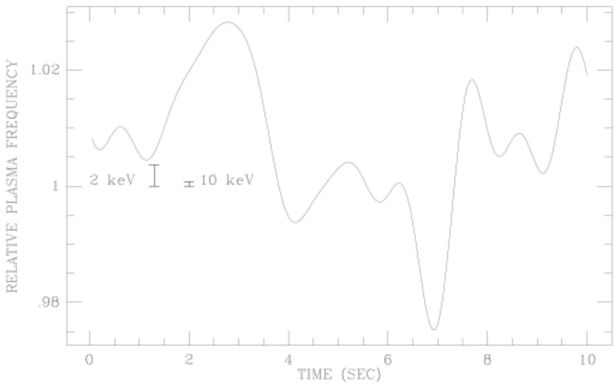

Fig. 1. A time series of plasma frequency fluctuations reconstructed from a spectrum from Celnikier et al (1987), together with bars showing the difference between the plasma frequency and the frequency which is resonant with electron beams of two energies.

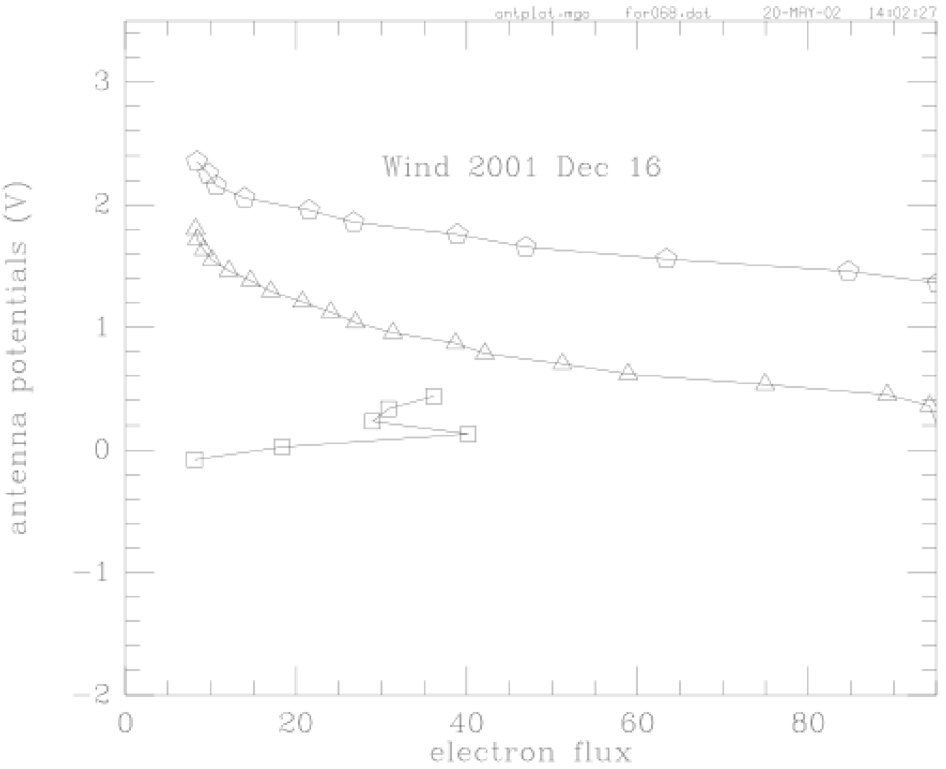

Fig. 2. Potential difference between the Wind spacecraft and its electric field antennas as a function of ambient electron flux.

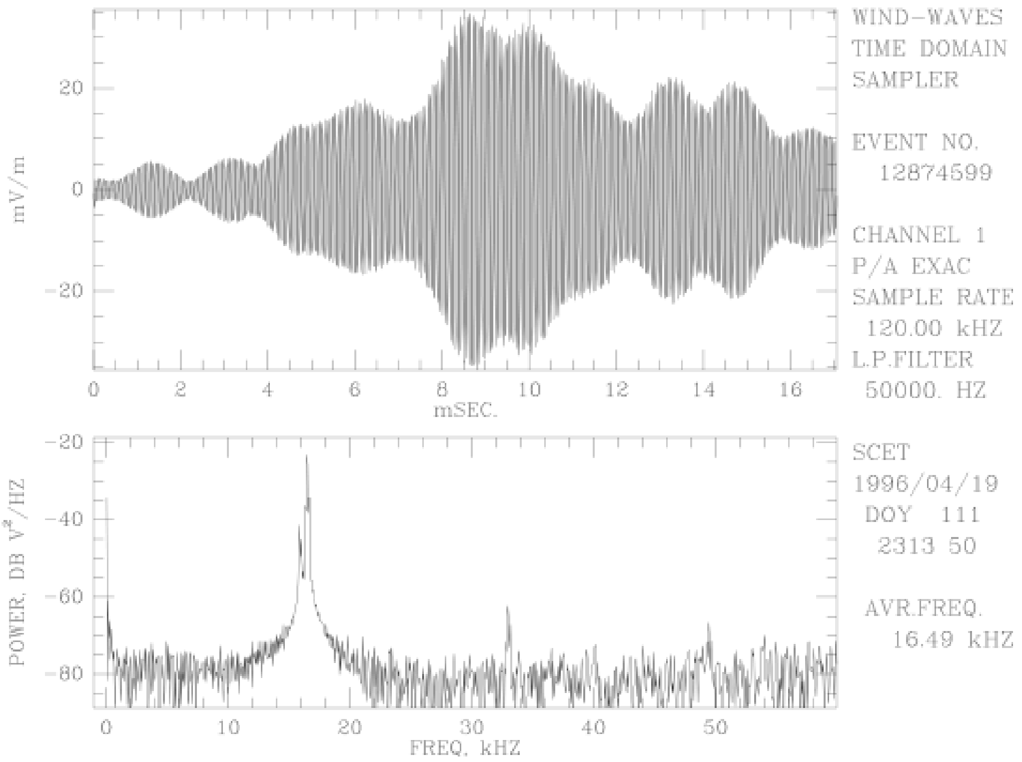

Fig. 3. A Langmuir wave observed with the TDS on Wind, showing a weak harmonic.

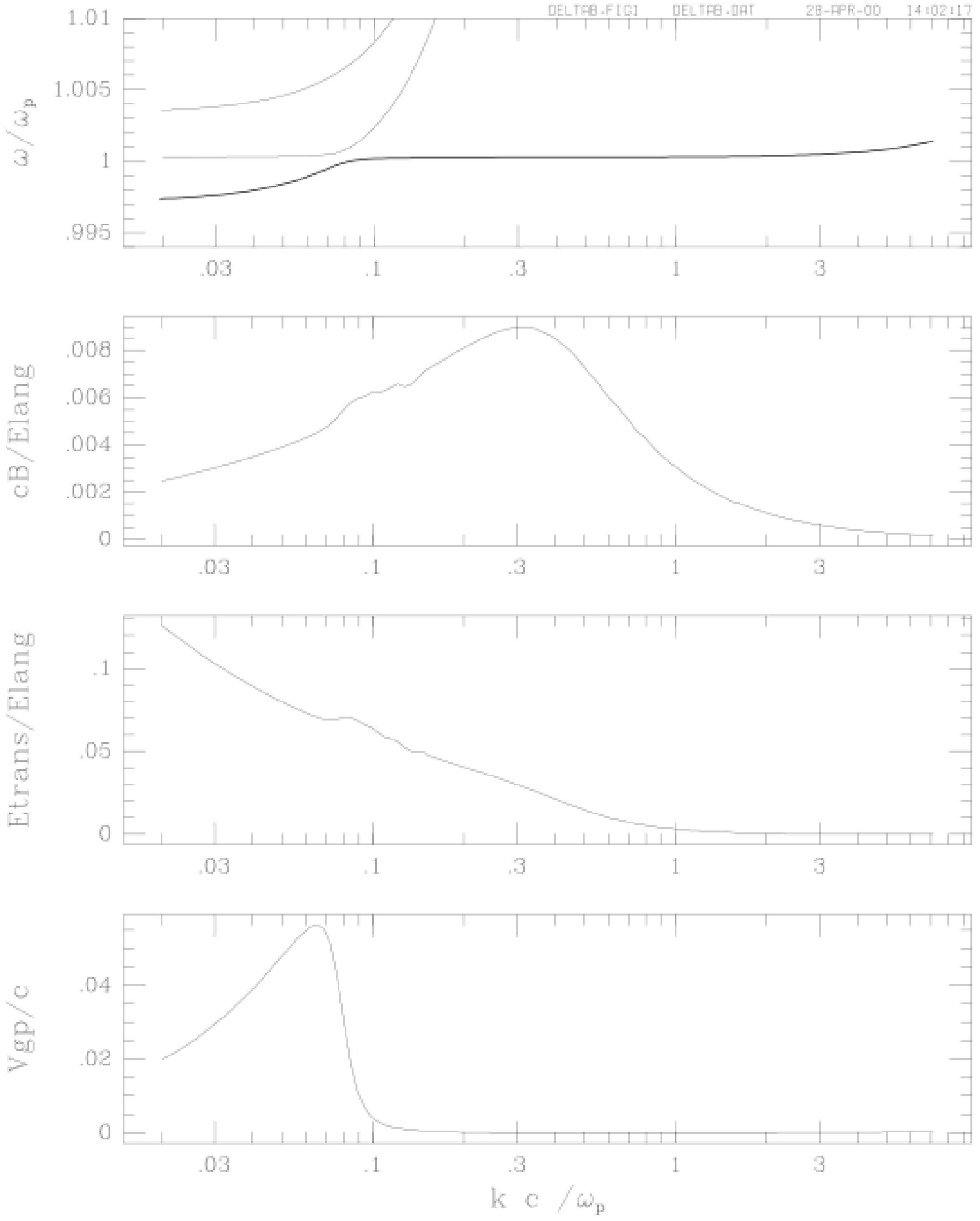

Fig. 4. Behavior of the electromagnetic fields of a Langmuir wave as it approaches a density ramp.

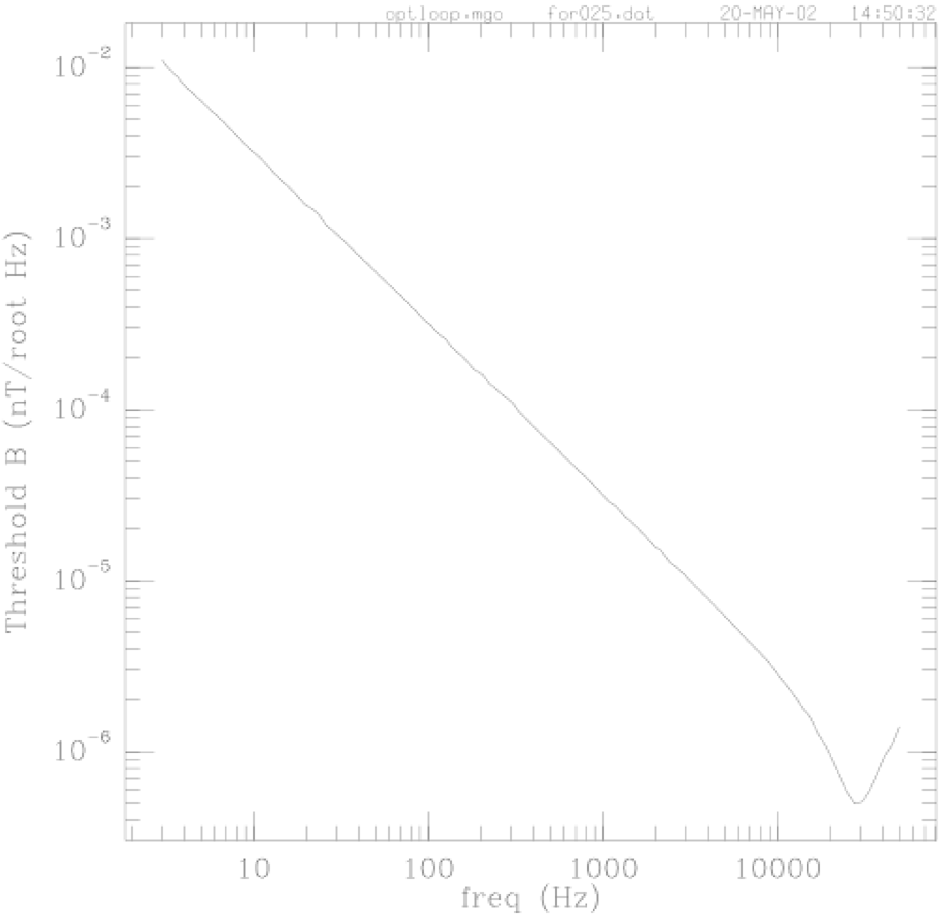

Fig. 5. Theoretical sensitivity of a loop antenna of 6 inches diameter, 200 gm mass.