Reminiscencias Científicas de Jicamarca

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INCOHERENT SCATTERING OF ELECTROMAGNETIC WAVES BY A PLASMA

A thesis presented

by

Ronald F. Woodman

to

The Division of Engineering and Applied Physics

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

in the subject of

Applied Physics

Harvard University

Cambridge, Massachusetts

March, 1967

Dispersión Incoherente de Ondas Electromagnéticas en un Plasma

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Resonancias giro-magnéticas

De la tesis de R. Woodman, pag. 110

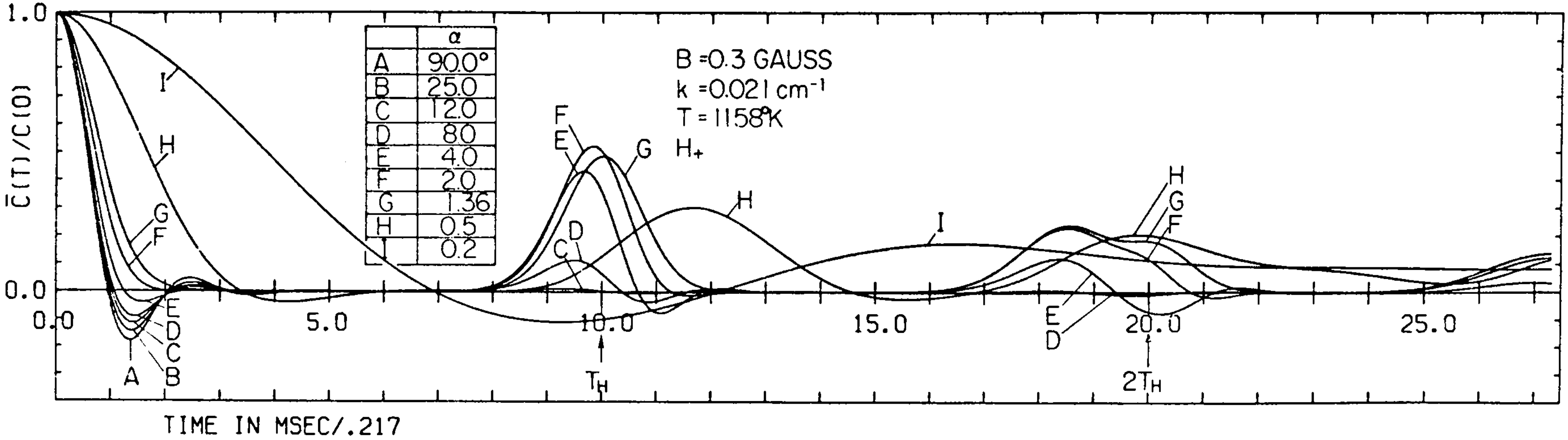

FIG. 7a. Autocorrelation function envelope $\bar{C}(\tau)$ for a $[H]^+$ plasma showing the effect of variations in the direction of the wave vector $\underset{\sim}{k}$ as it approaches the perpendicular to magnetic field ($\alpha = 0$). Collisionless model, other parameters as shown in the figure.

Excerpt from R. Woodman's PhD Thesis, 1967

Transcription from the original pages 3-4

Despite the extensive amount of theoretical work on the problem of incoherent scattering, this is still not complete. In the sense that, with the exception of two papers, one by Farley[5] and the other by Dougherty[6] which we shall briefly discuss, no one has included the effect of ion-ion interactions or so-called Coulomb collisions. Ionospheric plasmas, even in their most dense regions (F_{max} peak) have an affective ion-ion collision frequency of the order of 10 sec^{-1}, which is small compared with to other characteristic frequencies like the ion gyro-frequency and the thermal characteristic frequency (inverse of the time it takes an ion to travel one wavelength). These frequencies are of the order of 160 and 2000 radians/second (for $\lambda = 1.5$ meters) respectively. Thus, initially it appeared that neglecting the effect of this type of collision was justified. A more careful analysis shows that this is not the case, especially in predicting the effects of the magnetic field and ion gyro-resonance phenomena. A more careful analysis was stimulated by the fact that $[O]^+$ ion-gyro-resonances predicted by the collisionless model were not observed experimentally.

In the paper by Farley[5] mentioned above, he *estimated* the amount of probabilistic diffusion that any ion suffers after a gyro-period when subject to Coulomb collisions. From this he concluded, as we shall also see, that the effect of Coulomb collisions is indeed important and responsible for the failure of the experimental observations of oxygen gyro-resonances.

The other paper which considers the effect of Coulomb collisions is the one by Dougherty[6]. He presents a Fokker-Planck type collision model for the Bltzmann equation and its analytical solution. He considers a single component plasma with no self-consistent field. The incoherent scatter problem, regardless of the approach, requires the solution of Boltzmann-type equations, but the inclusion of at least two species (ions and electrons) and the inclusion of the self-consistent field. So in regards to this problem this paper can be considered as an important step towards its solution, but yet not complete. By discussing his solution, we also demonstrate the importance of the collision term for typical ionospheric parameters.

We were motivated to study the incoherent scatter problem (and the associated one of plasma density fluctuations) because of the incompleteness of the solutions offered so far in regard to the effect of Coulomb collisions. Our main goal is to investigate the effect of such collisions, mainly on the ion-gyro-resonances predicted by the collisionless theory. But, the contributions presented in this thesis are not limited to the inclusion of the effects of such collisions in our solution. We present a solution to the problem taking a new approach, starting from first principles, and removing in the process some of the limitations of the other approaches taken so far. We present a technique which formally could be used even in the case of non-homogeneous and non-stationary plasmas.

La tesis de Ronald F. Woodman

Es acerca de la teoría de la dispersión incoherente de ondas electromagnéticas en un plasma.

Emplea un método nunca empleado (antes ni después): Cálculo de la función de correlación como un problema de valor inicial.

La contribución más resaltante: El efecto de las colisiones de Culombio entre iones que explica la ausencia de giro-resonancias en los espectros medidos.

Durante los años 90 surgió un nuevo misterio:

Medición de temperaturas de iones mucho mayores que la temperatura de electrones.

Toma lenta de conciencia que el acertijo podía ser resuelto invocando colisiones de electrones.

37 años más tarde, en 2004 . . .

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2004

Journal of Atmospheric and Solar-Terrestrial Physics 66 (2004) 1521–1541

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

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On a proper electron collision frequency for a Fokker–Planck collision model with Jicamarca applications

Ronald F. Woodman

Instituto Geofísico del Perú, Lima, Peru

Abstract

Recently, Sulzer and Gonzalez (J. Geophys. Res. 104 (22) (1999) 22, 535) showed that the previously neglected effect of electron–electron and electron–ion Coulomb collisions has a significant impact on determining the incoherent scatter autocorrelation functions (IS-ACFs) observed at Jicamarca. Considering the physically and mathematically complicated nature of Coulomb collisions, they evaluated these effects with lengthy numerical computations which actually simulated the random electron trajectories for different possible electron velocities and for different state parameters of the medium, in a Monte Carlo-like simulation. Their conclusions have been readily accepted by the IS community for Jicamarca pointing angles very close to perpendicular to the magnetic field, but a controversy arose when the application of their results to angles around 3° off perpendicular to the magnetic field implied electron effective collision frequencies larger than the accepted values published in existing literature. Here we have taken a more analytical approach by using a simplified Fokker–Planck collision model with a velocity-independent collision frequency. We can reproduce the results of Sulzer and Gonzalez with this simplified analytical model, provided that an effective, velocity-independent collision frequency is used whose value depends upon the angle between the radar beam direction and the magnetic field. The physical reason for this seemingly strange result is that, for incoherent scatter, the relative importance of the Fokker–Planck friction and velocity diffusion terms changes with this angle. Furthermore, we estimated values for the electron frictional collision coefficient based on the more precise velocity-dependent one and found that, indeed, the large values are justified, supporting the previously controversial results of Sulzer and Gonzalez (1999).

1. Introduction

1.1. Some motivating history

Soon after the first successful ionospheric radar incoherent scatter (IS) experiment performed by Bowles (1958), using a 41 MHz radar near Havana, IL, a fairly complete and accurate theory was developed by different authors (e.g., Dougherty and Farley, 1960; Fejer, 1960; Salpeter, 1960; Hagfors, 1961) to explain the shape of the frequency spectrum of the incoherently backscattered signals. Moreover, the theories explained the surprising discovery from this first experiment that the dynamics of the ions controlled the shape of the frequency spectrum of the backscattered signals rather than the electrons. This was the opposite to what was expected from the seminal paper by Gordon (1958). As the theory rapidly developed, it became clear that state parameters of ionospheric plasma, other than just electron density and temperature, could be measured, given the theoretically predictable effect of these state parameters on the backscatter signal spectrum. The ions'

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2004

Acerca de una apropiada frequencia de colisiones de electrones para un modelo de colisiones de Fokker-Planck con aplicaciones a Jicamarca

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Appendix A

We have referred in the main text to Woodman's (1967) thesis as the basic reference for the incoherent scatter theory and formulas when the effects of Coulomb collisions and the magnetic field are included. The formulas were also used in obtaining the numerical results showing the correlation functions displayed in the relevant figures. The cited thesis includes the mathematical solution for the problem at hand: evaluating the statistical dynamics of relevant electron density fluctuations with a Fokker–Planck collision model. But since the thesis is not readily available to most readers, we reproduce here his approach to the problem and the relevant conclusions, including the computational algorithms used in producing the numerical results. We avoid the derivations, except when they help to obtain a better physical understanding of the conclusions. We have added some discussions and a figure, which was not in the original thesis, in order to better understand some of the concepts introduced here and in the main text.

The approach taken by Woodman (1967) differs from all other approaches to solve the plasma fluctuation problem. Using Lioville's equation, he proves rigorously that the space–time autocorrelation function of the electron density fluctuations in a homogeneous stationary plasma, given by

$$\rho(\mathbf{r},\tau) = \langle \dot{n}^{e}(\mathbf{x},t)\dot{n}^{e}(\mathbf{x}+\mathbf{r},t+\tau)\rangle, \qquad (A.1)$$

where $\dot{n}^{e}(\mathbf{x},t)$ stands for the random microscopic density of the medium, can be expressed as the product of two densities, namely

$$\rho(\mathbf{r},\tau) = n^{e} n'^{e}(\mathbf{r},\tau) \quad \text{for } \tau > 0. \qquad (A.2)$$

Here, n^{e} is the density of the actual plasma, and $n'^{e}(\mathbf{x},t)$ is the density of a hypothetical plasma having the same state parameters as the actual one, but which has been disturbed by placing an electron at $\mathbf{x}$, with a thermal velocity distribution of $\varphi^{e}(\mathbf{v})$ at time $t=0$. Then, one only needs to replace the real space, $\mathbf{x}$, and time, t, domains by the displacement, $\mathbf{r}$, and lag time, τ, respectively. For negative values of τ, we use the symmetrical properties of $\rho(\mathbf{r},\tau)=\rho(\mathbf{r},-\tau)$. Notice the conceptual diference between the microscopic random fluctuating densities denoted by a dotted-n ($\dot{n}(\mathbf{x},t)$) and the average densities, $n(\mathbf{x},t)$, defined, in general, by

$$n(\mathbf{x},t) = \int \mathrm{d}\mathbf{v}\, f(\mathbf{x},\mathbf{v},t). \qquad (A.3)$$

The equivalence relationship represented by Eq. (A.2) reminds us of Bayes' theorem. Indeed, its derivation is obtained using conditional probabilities but at the Lioville's equation level.

The equivalence property stated in Eq. (A.2) has the advantage of reducing the problem of evaluating the dynamics of a two-particle, two-time distribution function (e.g., the W_{11} and W_{12} of Rosenbluth and Rostoker (1962)), formally required to evaluate $\rho(\mathbf{r},\tau)$, to a more familiar one involving particle densities and one-particle distribution functions, $f(\mathbf{x},\mathbf{v},t)$, for which one has much more familiarity and for which there is extensive work in the literature. Other approaches, like the use of the Nyquist Theorem (Dougherty and Farley, 1960), also involve the one-particle distribution function. But it seems easier to have an intuitive physical picture for the solution of an initial value problem than for the frequency-dependent admittance of a plasma subjected to an external electric field. Woodman's (1967) approach has some resemblance to the dressed particle approach of Rosenbluth and Rostoker (1962), but the correspondence to an initial value problem stated above is unique.

With the use of (A.2), the problem is reduced, in mathematical terms, to an initial value problem involving the coupled integro-differential (Boltzmann-like) kinetic equations which model the phase-space–time evolution of the one-particle distribution functions, $f'^{\eta}(\mathbf{x},\mathbf{v},t)$, for all constituents, η, including the one for electrons, $f'^{e}(\mathbf{x},\mathbf{v},t)$ (see next section). In fact, they are all defined by the time evolution of their first-order perturbations, $f_1'^{\eta}(\mathbf{x},\mathbf{v},t)$, such that

$$f'^{\eta}(\mathbf{x},\mathbf{v},t) = n^{\eta}\varphi^{\eta}(\mathbf{v}) + f_1'^{\eta}(\mathbf{x},\mathbf{v},t). \qquad (A.4)$$

The first-order perturbation, under justifiable assumptions, satisfies the same kinetic equations as the total one-particle distribution functions, except for negligible second-order terms.

The initial conditions for the perturbations of the hypothetical plasma (note the primes used to differentiate hypothetical from real) are given by

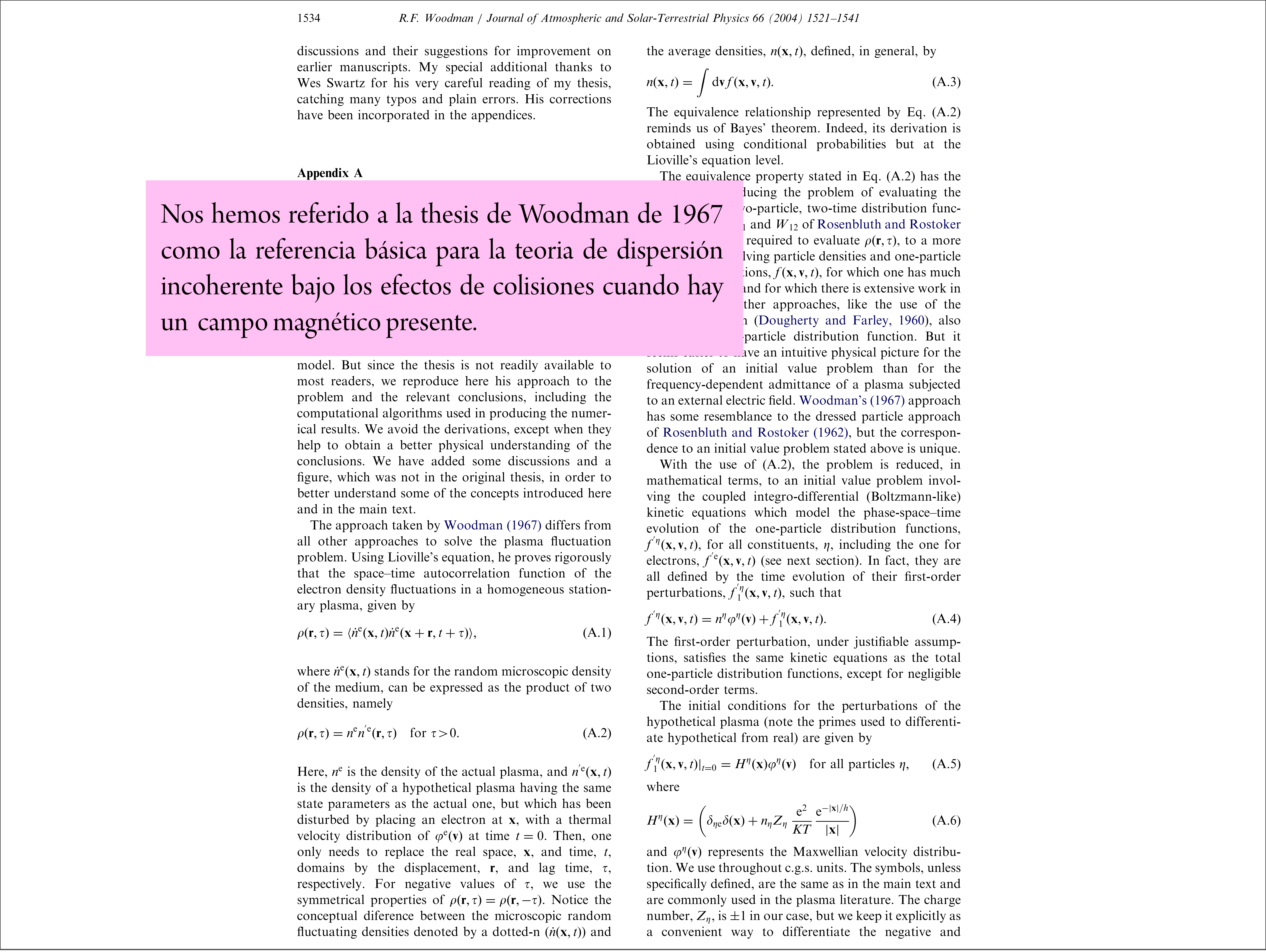
$$f_1'^{\eta}(\mathbf{x},\mathbf{v},t)|_{t=0} = H^{\eta}(\mathbf{x})\varphi^{\eta}(\mathbf{v}) \quad \text{for all particles } \eta, \qquad (A.5)$$

where

$$H^{\eta}(\mathbf{x}) = \left(\delta_{\eta e}\delta(\mathbf{x}) + n_{\eta} Z_{\eta}\frac{\mathrm{e}^{2}}{KT}\frac{\mathrm{e}^{-|\mathbf{x}|/h}}{|\mathbf{x}|}\right) \qquad (A.6)$$

and $\varphi^{\eta}(\mathbf{v})$ represents the Maxwellian velocity distribution. We use throughout c.g.s. units. The symbols, unless specifically defined, are the same as in the main text and are commonly used in the plasma literature. The charge number, Z_{η}, is ±1 in our case, but we keep it explicitly as a convenient way to differentiate the negative and

Nos hemos referido a la thesis de Woodman de 1967 como la referencia básica para la teoria de dispersión incoherente bajo los efectos de colisiones cuando hay un campo magnético presente.



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Epílogo (Provisionalmente)

El trabajo de Woodman de 2004 cementó teóricamente resultados obtenidos por Sulzer y González (1999) basados en simulaciones numéricas y les dió credibilidad.

Señala el camino a seguir para obtener una teoría satisfactoria (para los osados).

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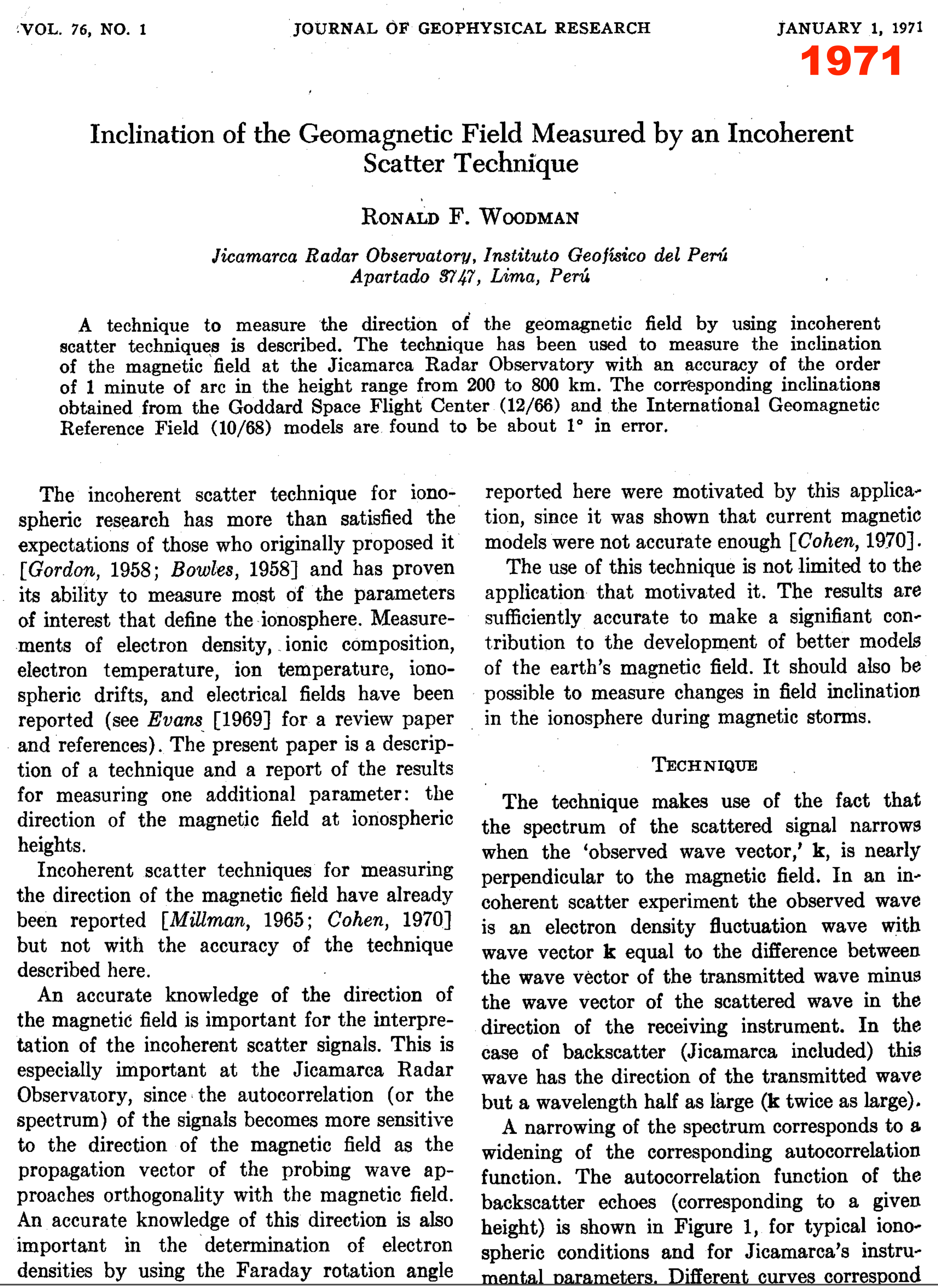

VOL. 76, NO. 1 JOURNAL OF GEOPHYSICAL RESEARCH JANUARY 1, 1971

1971

Inclination of the Geomagnetic Field Measured by an Incoherent Scatter Technique

RONALD F. WOODMAN

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Apartado 3747, Lima, Perú

A technique to measure the direction of the geomagnetic field by using incoherent scatter techniques is described. The technique has been used to measure the inclination of the magnetic field at the Jicamarca Radar Observatory with an accuracy of the order of 1 minute of arc in the height range from 200 to 800 km. The corresponding inclinations obtained from the Goddard Space Flight Center (12/66) and the International Geomagnetic Reference Field (10/68) models are found to be about 1° in error.

The incoherent scatter technique for ionospheric research has more than satisfied the expectations of those who originally proposed it [*Gordon*, 1958; *Bowles*, 1958] and has proven its ability to measure most of the parameters of interest that define the ionosphere. Measurements of electron density, ionic composition, electron temperature, ion temperature, ionospheric drifts, and electrical fields have been reported (see *Evans* [1969] for a review paper and references). The present paper is a description of a technique and a report of the results for measuring one additional parameter: the direction of the magnetic field at ionospheric heights.

Incoherent scatter techniques for measuring the direction of the magnetic field have already been reported [*Millman*, 1965; *Cohen*, 1970] but not with the accuracy of the technique described here.

An accurate knowledge of the direction of the magnetic field is important for the interpretation of the incoherent scatter signals. This is especially important at the Jicamarca Radar Observatory, since the autocorrelation (or the spectrum) of the signals becomes more sensitive to the direction of the magnetic field as the propagation vector of the probing wave approaches orthogonality with the magnetic field. An accurate knowledge of this direction is also important in the determination of electron densities by using the Faraday rotation angle reported here were motivated by this application, since it was shown that current magnetic models were not accurate enough [*Cohen*, 1970].

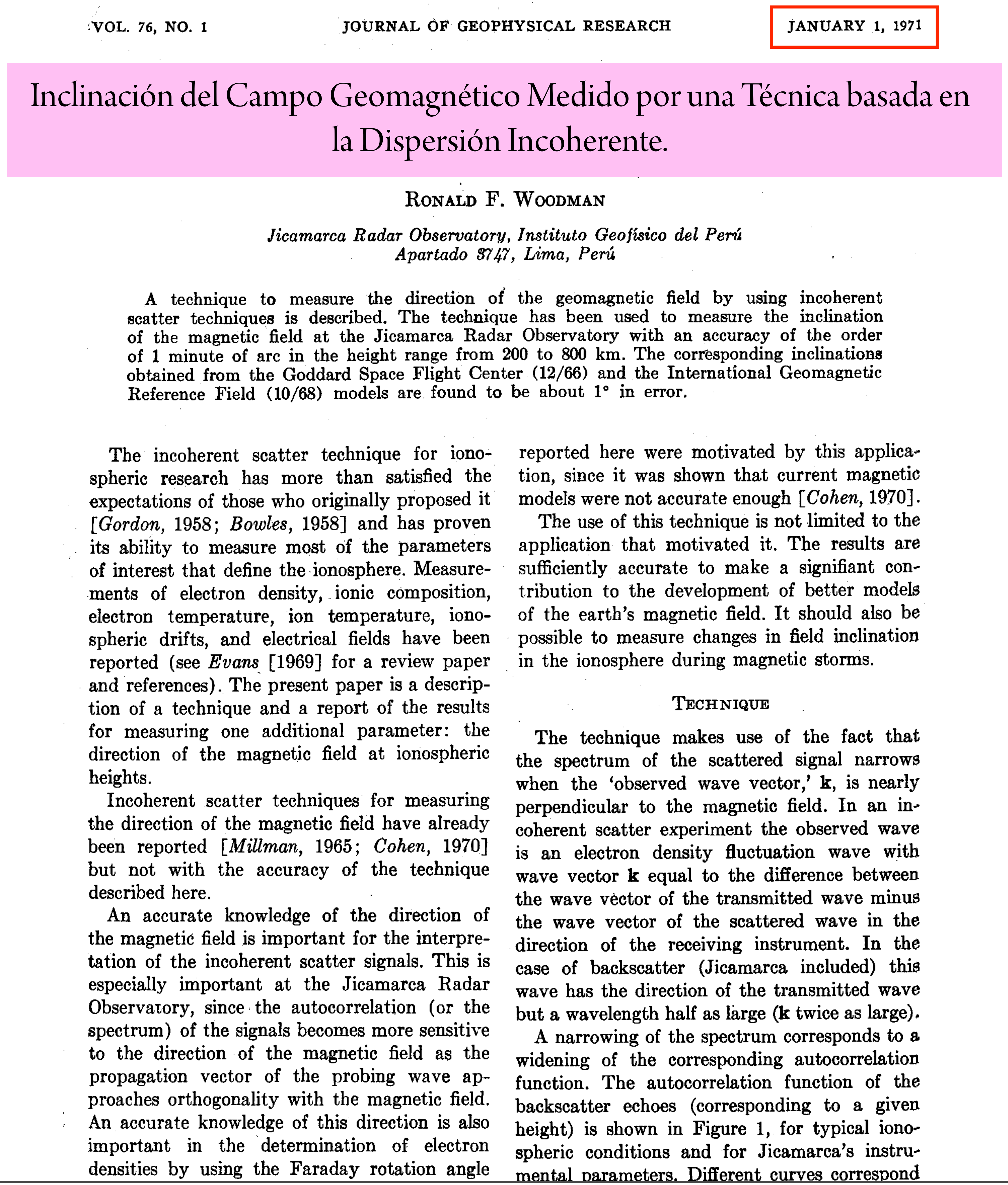
The use of this technique is not limited to the application that motivated it. The results are sufficiently accurate to make a signifiant contribution to the development of better models of the earth's magnetic field. It should also be possible to measure changes in field inclination in the ionosphere during magnetic storms.

TECHNIQUE

The technique makes use of the fact that the spectrum of the scattered signal narrows when the 'observed wave vector,' **k**, is nearly perpendicular to the magnetic field. In an incoherent scatter experiment the observed wave is an electron density fluctuation wave with wave vector **k** equal to the difference between the wave vector of the transmitted wave minus the wave vector of the scattered wave in the direction of the receiving instrument. In the case of backscatter (Jicamarca included) this wave has the direction of the transmitted wave but a wavelength half as large (**k** twice as large).

A narrowing of the spectrum corresponds to a widening of the corresponding autocorrelation function. The autocorrelation function of the backscatter echoes (corresponding to a given height) is shown in Figure 1, for typical ionospheric conditions and for Jicamarca's instrumental parameters. Different curves correspond

Inclinación del Campo Geomagnético Medido por una Técnica basada en la Dispersión Incoherente.



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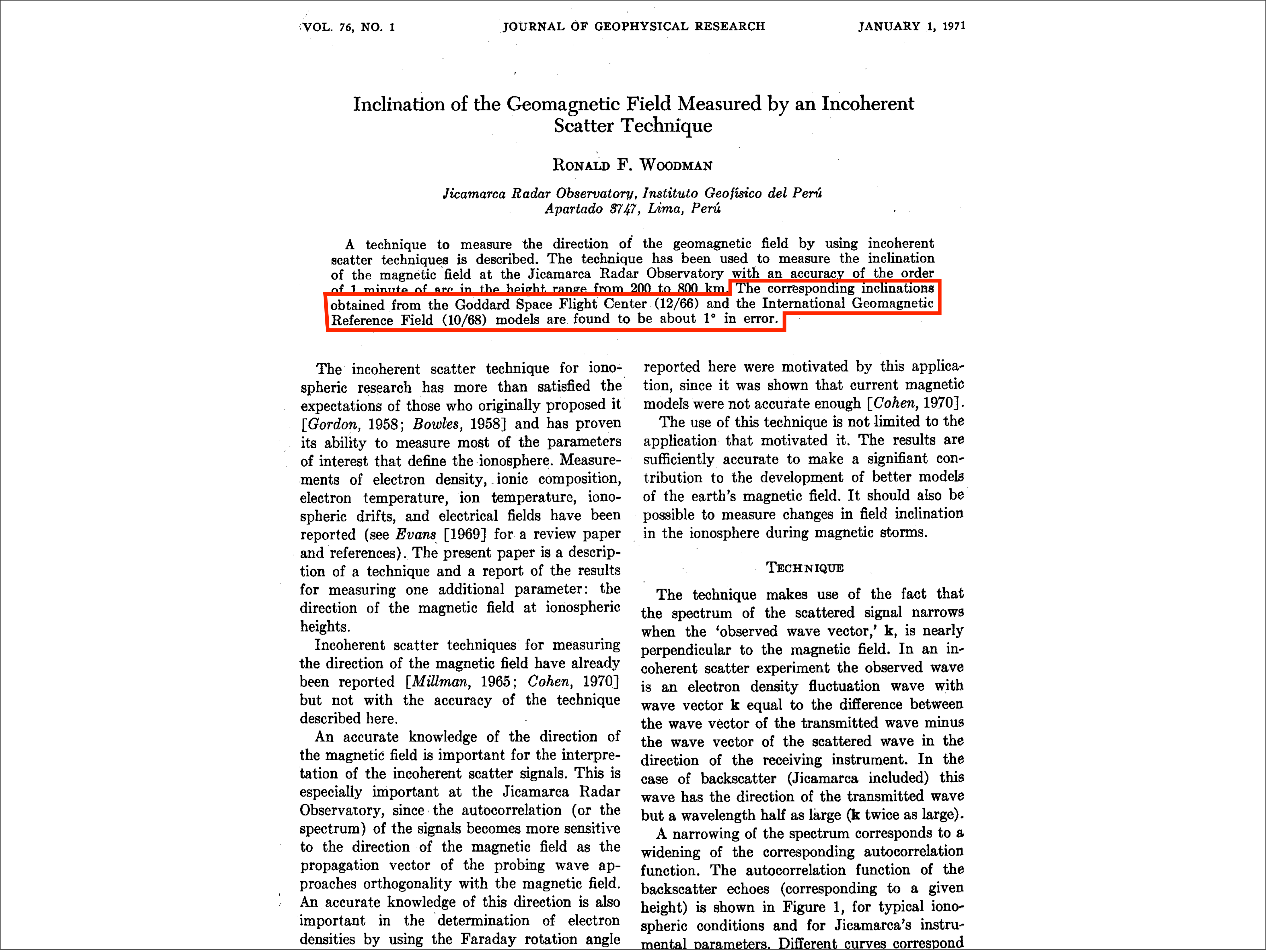

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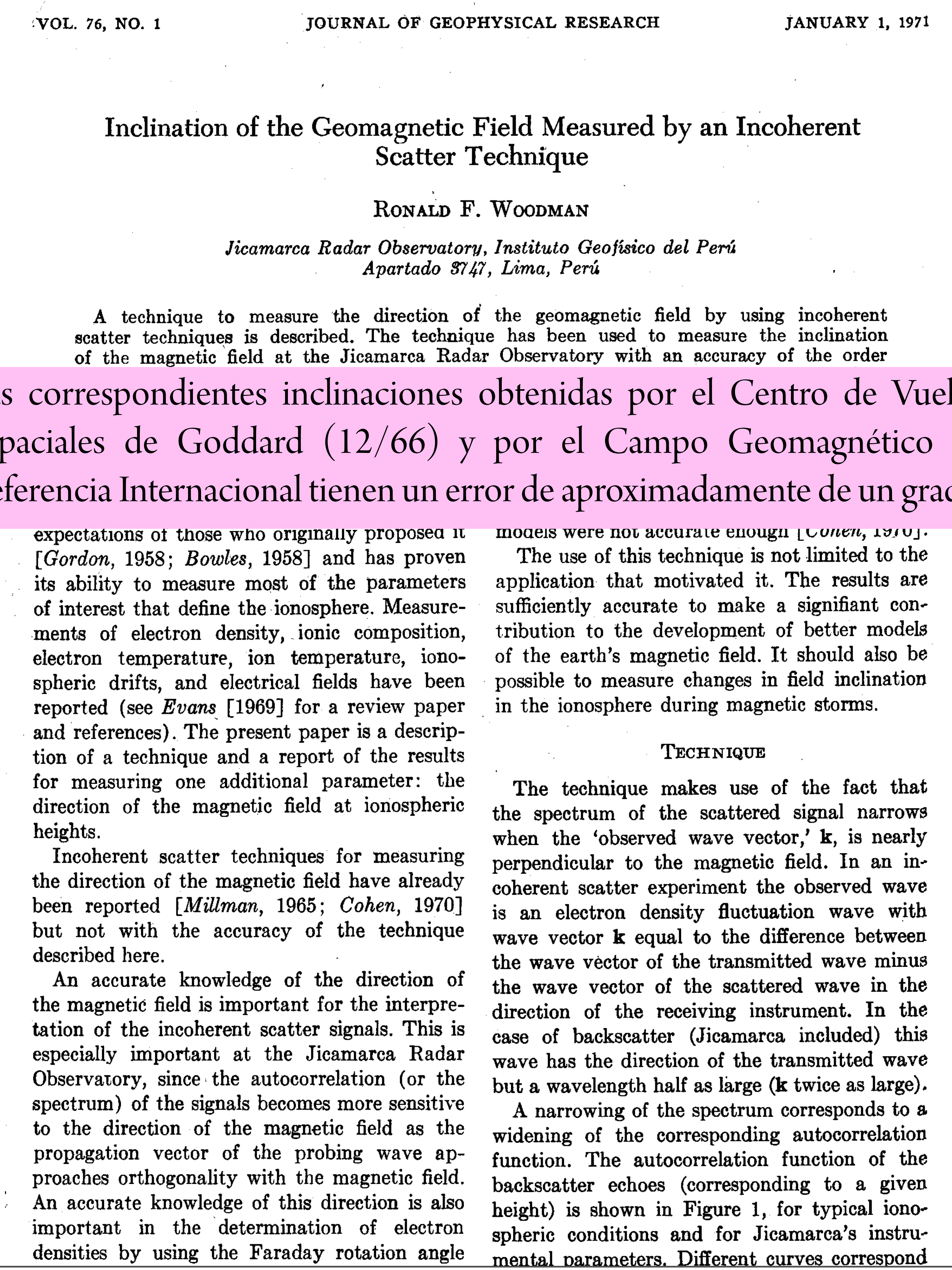
TECHNIQUE

The technique makes use of the fact that the spectrum of the scattered signal narrows when the 'observed wave vector,' **k**, is nearly perpendicular to the magnetic field. In an incoherent scatter experiment the observed wave is an electron density fluctuation wave with wave vector **k** equal to the difference between the wave vector of the transmitted wave minus the wave vector of the scattered wave in the direction of the receiving instrument. In the case of backscatter (Jicamarca included) this wave has the direction of the transmitted wave but a wavelength half as large (**k** twice as large).

A narrowing of the spectrum corresponds to a widening of the corresponding autocorrelation function. The autocorrelation function of the backscatter echoes (corresponding to a given height) is shown in Figure 1, for typical ionospheric conditions and for Jicamarca's instrumental parameters. Different curves correspond

Las correspondientes inclinaciones obtenidas por el Centro de Vuelos Espaciales de Goddard (12/66) y por el Campo Geomagnético de Referencia Internacional tienen un error de aproximadamente de un grado.



VOL. 76, NO. 1 JOURNAL OF GEOPHYSICAL RESEARCH JANUARY 1, 1971

Inclination of the Geomagnetic Field Measured by an Incoherent Scatter Technique

RONALD F. WOODMAN

Jicamarca Radar Observatory, Instituto Geofísico del Perú
Apartado 3747, Lima, Perú

A technique to measure the direction of the geomagnetic field by using incoherent scatter techniques is described. The technique has been used to measure the inclination of the magnetic field at the Jicamarca Radar Observatory with an accuracy of the order

expectations of those who originally proposed it [*Gordon*, 1958; *Bowles*, 1958] and has proven its ability to measure most of the parameters of interest that define the ionosphere. Measurements of electron density, ionic composition, electron temperature, ion temperature, ionospheric drifts, and electrical fields have been reported (see *Evans* [1969] for a review paper and references). The present paper is a description of a technique and a report of the results for measuring one additional parameter: the direction of the magnetic field at ionospheric heights.

Incoherent scatter techniques for measuring the direction of the magnetic field have already been reported [*Millman*, 1965; *Cohen*, 1970] but not with the accuracy of the technique described here.

An accurate knowledge of the direction of the magnetic field is important for the interpretation of the incoherent scatter signals. This is especially important at the Jicamarca Radar Observatory, since the autocorrelation (or the spectrum) of the signals becomes more sensitive to the direction of the magnetic field as the propagation vector of the probing wave approaches orthogonality with the magnetic field. An accurate knowledge of this direction is also important in the determination of electron densities by using the Faraday rotation angle

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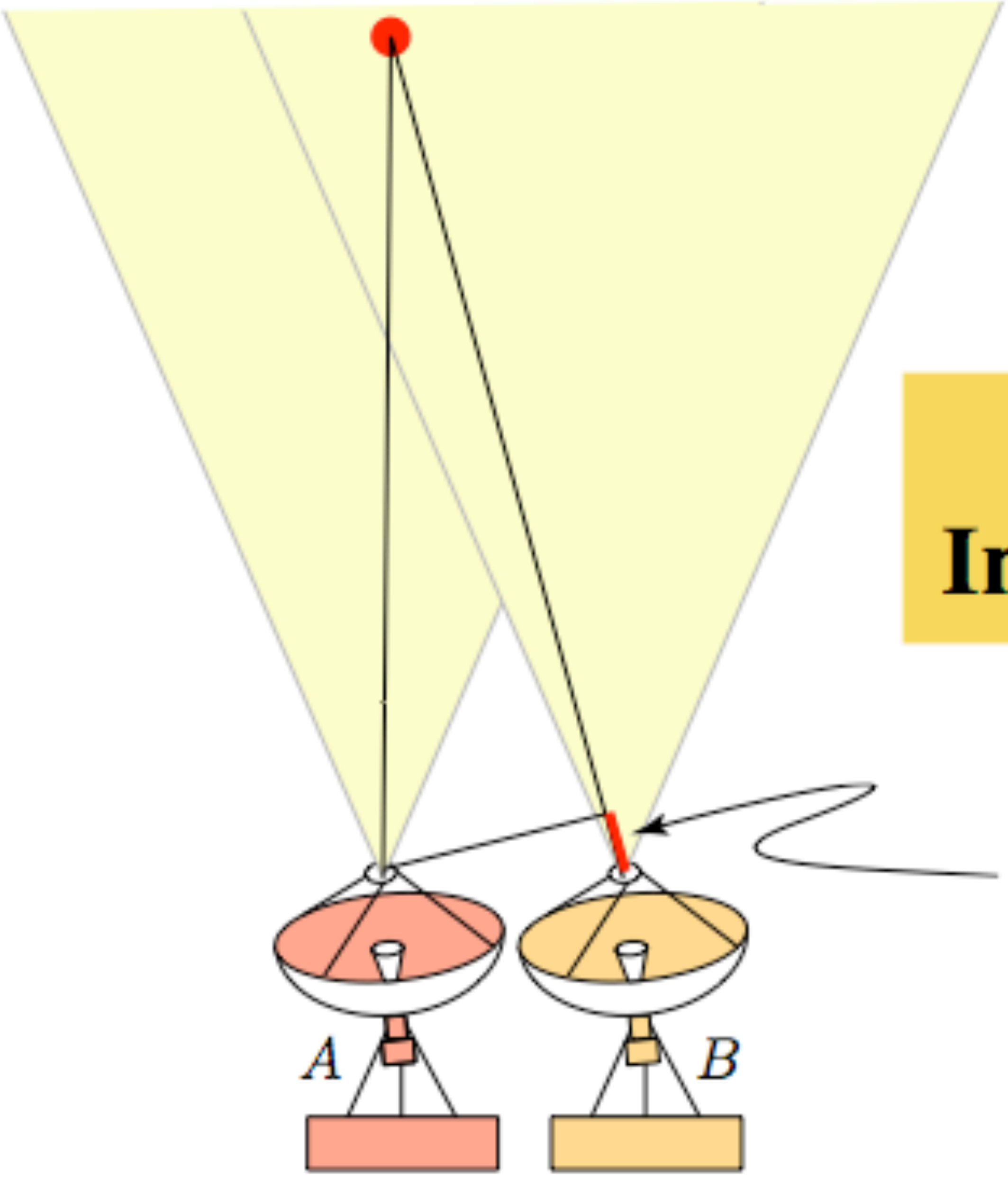
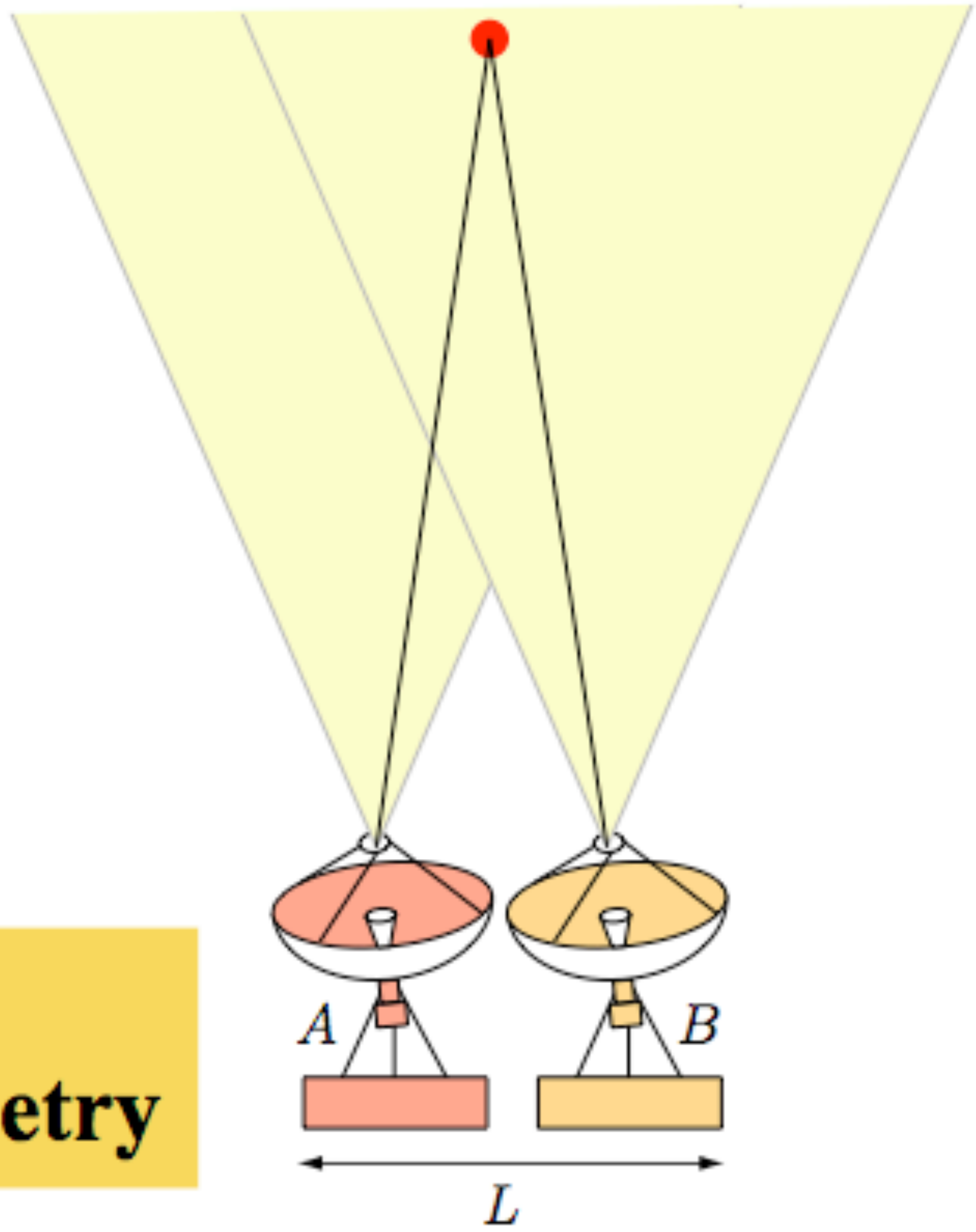
Radar Interferometry

Assume there is a discrete scatterer ● equidistant from both antennas. The scattered signal will arrive with the same phase to the two antennas.



$$\frac{2\pi L \sin\theta}{\lambda}$$



When the scatterer is off center the signals arriving to each antenna will have a phase difference which can be related unambiguously to the position of the scatterer given by θ.

10 años más tarde, en 1981 . . .

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86. NO. A3, PAGES 1467–1472, MARCH 1, 1981

1981

Radar Interferometry: A New Technique for Studying Plasma Turbulence in the Ionosphere

D. T. FARLEY, H. M. IERKIC, AND B. G. FEJER

School of Electrical Engineering, Cornell University, Ithaca, New York 14853

A new radar interferometer technique has been developed and used successfully at the Jicamarca Radio Observatory in Peru to study the strong nighttime plasma turbulence in the equatorial electrojet. The technique represents a major step forward in radar probing of turbulent irregularities such as (but not limited to) those in the electrojet. In many situations it provides far more information than previous Doppler measurements. We form the cross spectrum of the backscattered signals received from approximately overhead on two antennas, separated in this case along an east-west baseline, as well as the individual power spectra. From the phase of the cross spectrum at different Doppler frequencies we can determine the individual positions of plasma wave packets propagating vertically with different velocities, and we find, for example, that oppositely propagating waves always come from distinctly separated regions. The data allow us to study the eddy structure within the electrojet in far more detail than hitherto possible, and by using the irregularity patches as tracers and following their east-west motion, we can obtain a vertical profile of drift velocity. Our first observations of this sort have shown that at night the vertical Doppler velocity at times may substantially exceed the mean horizontal velocity of the patch and the small horizontal velocity near the top and bottom of the layer may actually be westward when the main motion is eastward.

INTRODUCTION

This paper describes an important new radar scattering technique developed at Jicamarca for studying two-dimensional ionospheric plasma turbulence and presents some of the first results obtained from investigations of the equatorial electrojet. More detailed discussion of observations of the irregularities in the electrojet and in the equatorial *F* region will be given in subsequent publications.

The technique is an extension of a method described by *Woodman* [1971], who showed that a radar interferometer could accurately determine the position of a highly localized scattering region. Using the north and south quarters of the large 50-MHz, vertically pointing array at Jicamarca, he was able to measure very precisely the locus of points in the *F* region at which the line of sight from the radar was perpendicular to the magnetic field, since the scattering irregularities are highly field aligned. He showed that the inclination angles of the then existing magnetic field models were in error by roughly 1°.

The technique we shall describe here is similar, except that the baseline is east-west and we also make use of the spectral information in the scattered signal. The method works when the scattering region is highly structured, or more specifically, when the received scattered signal within a particular small interval of Doppler shift corresponds to a small range of angular positions within the scattering volume. We transmit using the entire Jicamarca array (48 λ × 48 λ), pointed approximately vertically and perpendicular to the magnetic field, and receive separately on the east and west quarters. Each signal is sampled at a number of ranges and then later Fourier-transformed. Next we compute the normalized cross spectrum of the two signals for each range and average the results. For

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Our first observations were made during the night, when the electrojet is highly structured, and the results exceeded our expectations. We found that at least a portion of the echo at this time usually does indeed come from a few (1–3 typically) discrete locations, even when most of the echo is diffuse. Furthermore, the east-west motion of the discrete echoing centers through the scattering volume can be tracked. We thus can determine some characteristics of the large eddies in which the short-wavelength irregularities are imbedded and can also obtain profiles of drift velocity as a function of altitude and time, using the irregularities as tracers and assuming that they move with the background plasma. These results add new information to that obtained in our most recent previous study of the nighttime turbulence [*Farley et al.*, 1978]. The general properties and current theories of the electrojet instabilities are discussed in reviews by *Farley* [1979], *Fejer* [1979], and *Fejer and Kelley* [1980]. Further details concerning some of the material presented here are given by *Ierkic* [1980].

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Interferometría de Radar: Una técnica Nueva para Estudiar la Turbulencia del Plasma en la Ionósfera

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La técnica es una extensión de un método descrito por Woodman (1971), quién demostró que un interferómetro de radar podía determinar muy exactamente la posición de una región dispersante muy pequeña.

Y aún 20 años más tarde, en 1991 . . .

GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 1, PAGES 41-44, JANUARY 1991

1991

RADAR INTERFEROMETRIC IMAGING OF FIELD-ALIGNED PLASMA IRREGULARITIES IN THE EQUATORIAL ELECTROJET

Erhan Kudeki and Fahri Sürücü

Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign

Abstract. A multiple-receiver radar technique for imaging the spatial distribution of ionospheric plasma irregularities is introduced and demonstrated with equatorial electrojet data obtained at the Jicamarca Radio Observatory. The images obtained with a few seconds time resolution enable the monitoring of the temporal evolution of the irregularity structures within the radar field of view. Daytime electrojet images contain signatures of localized irregularity patches which drift in the east-west direction at about the ion-acoustic velocity.

1 Introduction

In this paper we introduce a radar interferometric imaging (RII) technique and illustrate its application with equatorial electrojet data collected at the Jicamarca Radio Observatory near Lima, Peru. The RII technique is a natural outgrowth of the radar interferometry (RI) technique pioneered by Farley and co-workers at Jicamarca [e.g., *Farley et al.,* 1981] and the post-statistics steering technique introduced in *Kudeki and Woodman* [1990]. It may also be viewed as an extension of radio astronomic imaging [e.g., *Thompson et al.,* 1986] to include active illumination (radar transmitter) and Doppler sorting. The RII technique requires coherent detection of the radar echoes with multiple receiving antennas forming a uniform sequence of receiver-pair baselines. Fourier transforming the receiver-pair cross-spectrum estimates from the baseline domain to angular space we obtain a brightness spectrum which may be regarded as the multi-color (Doppler sorted) spatial image of the ionospheric irregularities responsible for the echoes. The technique enables monitoring the temporal evolution of the spatial irregularity structures within the radar field of view with a time resolution of a few seconds.

The RII technique is described in Section 2. In Section 3 we present some preliminary images of equatorial electrojet irregularities obtained with the RII technique.

2 Radar Interferometric Imaging

Consider the cross-correlation function

$$R(\tau,\alpha,\beta;t,\vec{x}_o) \equiv < s(t,\vec{x}_o)s^*(t+\tau,\vec{x}_o+\alpha\hat{x}+\beta\hat{y}) > \quad (1)$$

mitter. In (1), $\hat{x}$ and $\hat{y}$ are orthogonal unit vectors, and the position vector magnitudes are measured in units of radar carrier wavelength $\lambda_o \equiv c/f_o$, where c is the speed of light, and f_o is the carrier frequency. Assuming a pulsed modulation of the transmitted carrier with some interpulse period T and the quasi-stationarity of the scattering irregularities, the cross-correlation function (1) should be periodic in t with a period T, with each value of t labeling some radar range $r \equiv ct/2$. Focusing our attention on radar returns from some fixed range r in the far field, and assuming the quasi-homogeneity of the return signals we drop the labels t and $\vec{x}_o$, and express the cross-correlation function $R(\tau,\alpha,\beta)$ as the Fourier transform of a *brightness spectrum* $B(f,\theta_x,\theta_y)$ via

$$R(\tau,\alpha,\beta) = \int df\, e^{j2\pi f\tau}\, V(f,\alpha,\beta), \quad (2)$$

where

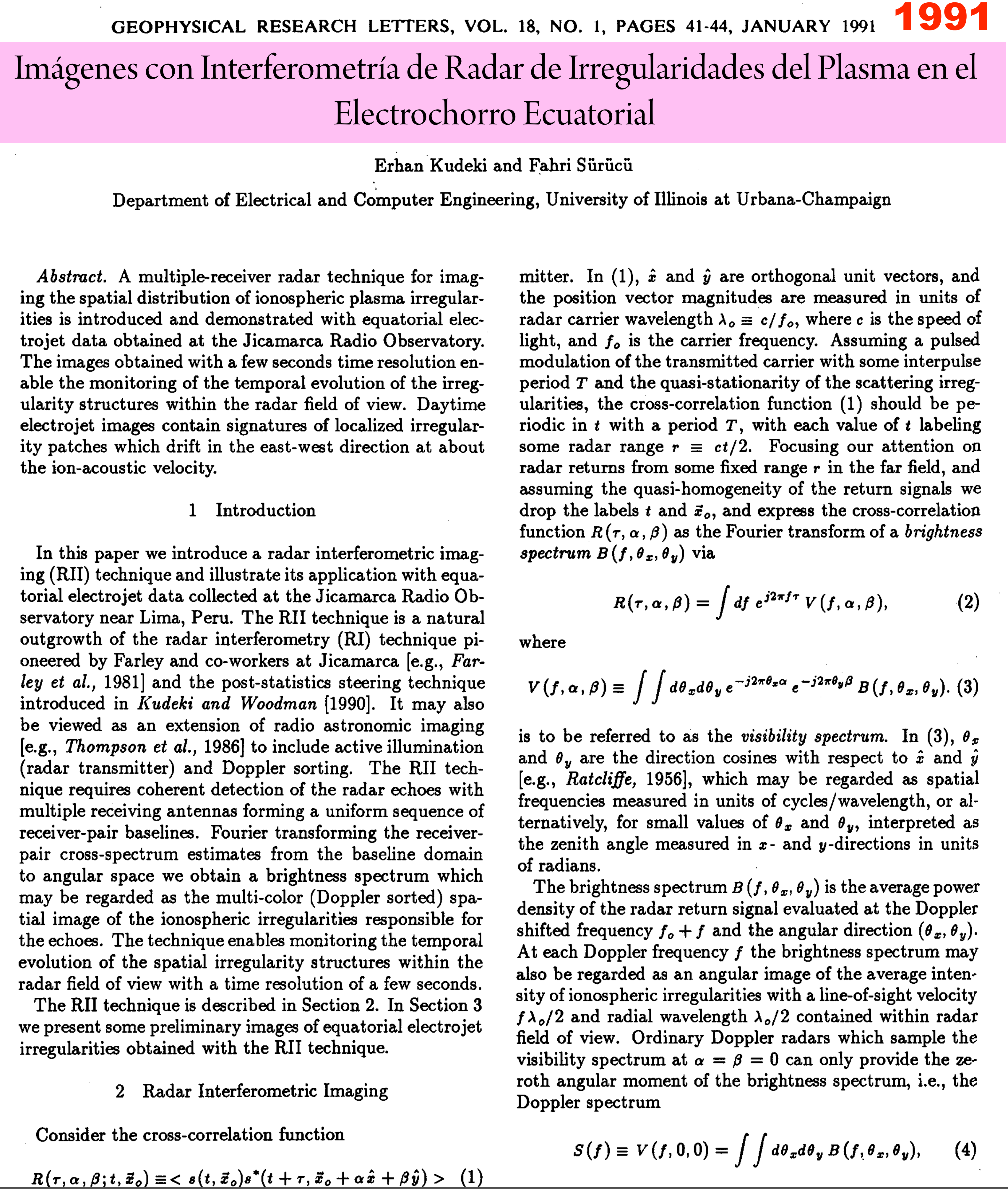
$$V(f,\alpha,\beta) \equiv \int\int d\theta_x d\theta_y\, e^{-j2\pi\theta_x\alpha}\, e^{-j2\pi\theta_y\beta}\, B(f,\theta_x,\theta_y). \quad (3)$$

is to be referred to as the *visibility spectrum.* In (3), θ_x and θ_y are the direction cosines with respect to $\hat{x}$ and $\hat{y}$ [e.g., *Ratcliffe,* 1956], which may be regarded as spatial frequencies measured in units of cycles/wavelength, or alternatively, for small values of θ_x and θ_y, interpreted as the zenith angle measured in x- and y-directions in units of radians.

The brightness spectrum $B(f,\theta_x,\theta_y)$ is the average power density of the radar return signal evaluated at the Doppler shifted frequency f_o+f and the angular direction (θ_x,θ_y). At each Doppler frequency f the brightness spectrum may also be regarded as an angular image of the average intensity of ionospheric irregularities with a line-of-sight velocity $f\lambda_o/2$ and radial wavelength $\lambda_o/2$ contained within radar field of view. Ordinary Doppler radars which sample the visibility spectrum at $\alpha = \beta = 0$ can only provide the zeroth angular moment of the brightness spectrum, i.e., the Doppler spectrum

$$S(f) \equiv V(f,0,0) = \int\int d\theta_x d\theta_y\, B(f,\theta_x,\theta_y), \quad (4)$$

which offers no information about how the scattering ir-



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$$V(f,\alpha,\beta) \equiv \int\!\!\int d\theta_x d\theta_y\, e^{-j2\pi\theta_x\alpha}\, e^{-j2\pi\theta_y\beta}\, B(f,\theta_x,\theta_y). \quad (3)$$

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GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 1, PAGES 41-44, JANUARY 1991

RADAR INTERFEROMETRIC IMAGING OF FIELD-ALIGNED PLASMA IRREGULARITIES IN THE EQUATORIAL ELECTROJET

Erhan Kudeki and Fahri Sürücü

Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign

Abstract. A multiple-receiver radar technique for imaging the spatial distribution of ionospheric plasma irregularities is introduced and demonstrated with equatorial electrojet data obtained at the Jicamarca Radio Observatory. The images obtained with a few seconds time resolution enable the monitoring of the temporal evolution of the irregularity structures within the radar field of view. Daytime electrojet images contain signatures of localized irregularity patches which drift in the east-west direction at about the ion-acoustic velocity.

1 Introduction

In this paper we introduce a radar interferometric imaging (RII) technique and illustrate its application with equatorial electrojet data collected at the Jicamarca Radio Observatory near Lima, Peru. The RII technique is a natural outgrowth of the radar interferometry (RI) technique pioneered by Farley and co-workers at Jicamarca [e.g., *Farley et al.,* 1981] and the post-statistics steering technique introduced in *Kudeki and Woodman* [1990]. It may also be viewed as an extension of radio astronomic imaging [e.g., *Thompson et al.,* 1986] to include active illumination (radar transmitter) and Doppler sorting. The RII technique requires coherent detection of the radar echoes with multiple receiving antennas forming a uniform sequence of receiver-pair baselines. Fourier transforming the receiver-pair cross-spectrum estimates from the baseline domain to angular space we obtain a brightness spectrum which may be regarded as the multi-color (Doppler sorted) spatial image of the ionospheric irregularities responsible for the echoes. The technique enables monitoring the temporal evolution of the spatial irregularity structures within the radar field of view with a time resolution of a few seconds.

The RII technique is described in Section 2. In Section 3 we present some preliminary images of equatorial electrojet irregularities obtained with the RII technique.

2 Radar Interferometric Imaging

Consider the cross-correlation function

$$R(\tau,\alpha,\beta;t,\vec{x}_o) \equiv < s(t,\vec{x}_o)s^*(t+\tau,\vec{x}_o+\alpha\hat{x}+\beta\hat{y}) > \quad (1)$$

mitter. In (1), $\hat{x}$ and $\hat{y}$ are orthogonal unit vectors, and the position vector magnitudes are measured in units of radar carrier wavelength $\lambda_o \equiv c/f_o$, where c is the speed of light, and f_o is the carrier frequency. Assuming a pulsed modulation of the transmitted carrier with some interpulse period T and the quasi-stationarity of the scattering irregularities, the cross-correlation function (1) should be periodic in t with a period T, with each value of t labeling some radar range $r \equiv ct/2$. Focusing our attention on radar returns from some fixed range r in the far field, and assuming the quasi-homogeneity of the return signals we drop the labels t and $\vec{x}_o$, and express the cross-correlation function $R(\tau,\alpha,\beta)$ as the Fourier transform of a *brightness spectrum* $B(f,\theta_x,\theta_y)$ via

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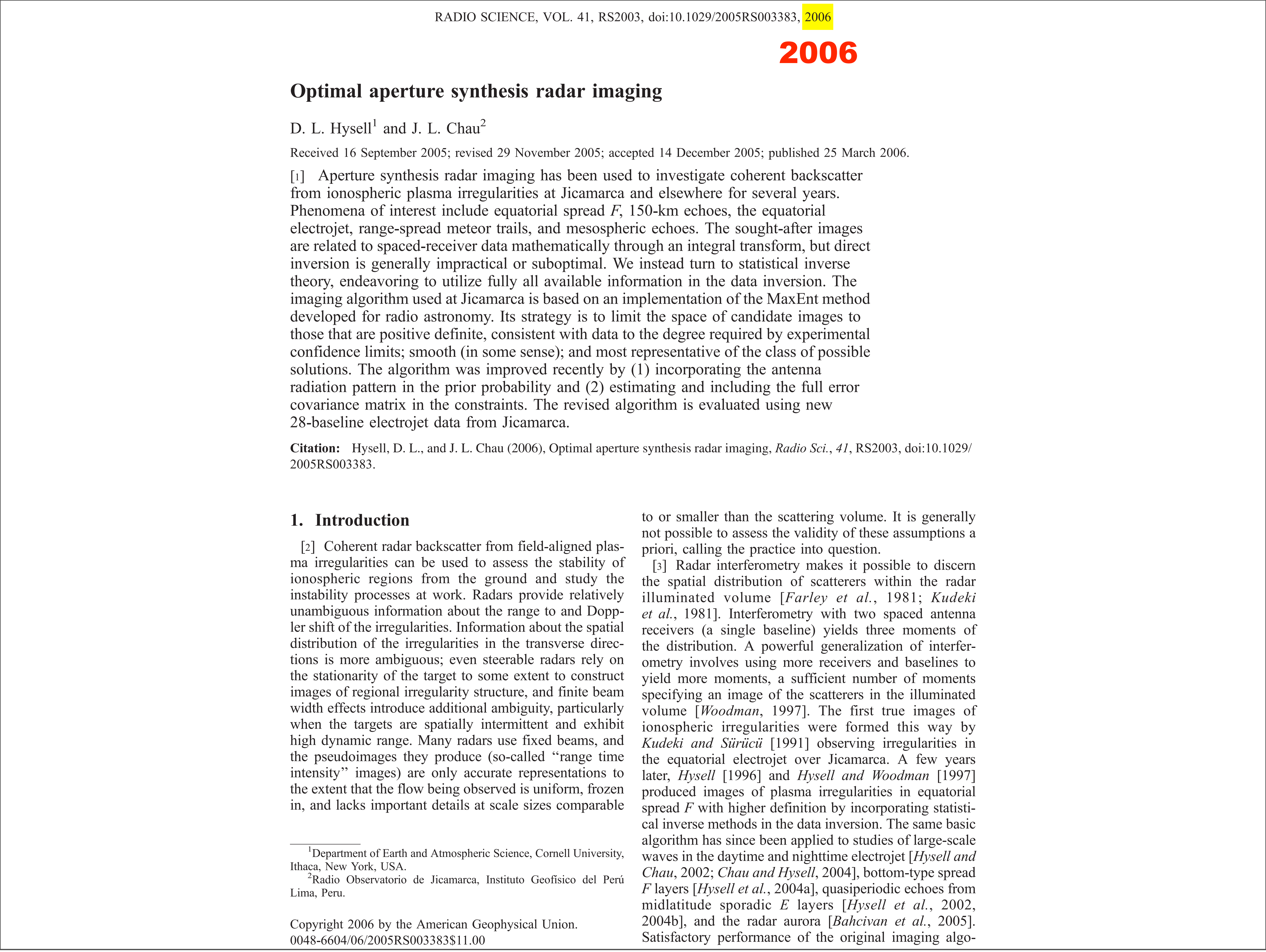
La técnica de Imágenes Interferométricas con Radar (IIR) es una extensión natural de la técnica interferométrica con radar de Farley et al. (1981) y la técnica de apuntamiento post-estadístico de Kudeki y Woodman (1990).



RADIO SCIENCE, VOL. 41, RS2003, doi:10.1029/2005RS003383, 2006

2006

Optimal aperture synthesis radar imaging

D. L. Hysell[1] and J. L. Chau[2]

Received 16 September 2005; revised 29 November 2005; accepted 14 December 2005; published 25 March 2006.

[1] Aperture synthesis radar imaging has been used to investigate coherent backscatter from ionospheric plasma irregularities at Jicamarca and elsewhere for several years. Phenomena of interest include equatorial spread *F*, 150-km echoes, the equatorial electrojet, range-spread meteor trails, and mesospheric echoes. The sought-after images are related to spaced-receiver data mathematically through an integral transform, but direct inversion is generally impractical or suboptimal. We instead turn to statistical inverse theory, endeavoring to utilize fully all available information in the data inversion. The imaging algorithm used at Jicamarca is based on an implementation of the MaxEnt method developed for radio astronomy. Its strategy is to limit the space of candidate images to those that are positive definite, consistent with data to the degree required by experimental confidence limits; smooth (in some sense); and most representative of the class of possible solutions. The algorithm was improved recently by (1) incorporating the antenna radiation pattern in the prior probability and (2) estimating and including the full error covariance matrix in the constraints. The revised algorithm is evaluated using new 28-baseline electrojet data from Jicamarca.

Citation: Hysell, D. L., and J. L. Chau (2006), Optimal aperture synthesis radar imaging, *Radio Sci.*, *41*, RS2003, doi:10.1029/2005RS003383.

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[2] Coherent radar backscatter from field-aligned plasma irregularities can be used to assess the stability of ionospheric regions from the ground and study the instability processes at work. Radars provide relatively unambiguous information about the range to and Doppler shift of the irregularities. Information about the spatial distribution of the irregularities in the transverse directions is more ambiguous; even steerable radars rely on the stationarity of the target to some extent to construct images of regional irregularity structure, and finite beam width effects introduce additional ambiguity, particularly when the targets are spatially intermittent and exhibit high dynamic range. Many radars use fixed beams, and the pseudoimages they produce (so-called “range time intensity” images) are only accurate representations to the extent that the flow being observed is uniform, frozen in, and lacks important details at scale sizes comparable to or smaller than the scattering volume. It is generally not possible to assess the validity of these assumptions a priori, calling the practice into question.

[3] Radar interferometry makes it possible to discern the spatial distribution of scatterers within the radar illuminated volume [*Farley et al.*, 1981; *Kudeki et al.*, 1981]. Interferometry with two spaced antenna receivers (a single baseline) yields three moments of the distribution. A powerful generalization of interferometry involves using more receivers and baselines to yield more moments, a sufficient number of moments specifying an image of the scatterers in the illuminated volume [*Woodman*, 1997]. The first true images of ionospheric irregularities were formed this way by *Kudeki and Sürücü* [1991] observing irregularities in the equatorial electrojet over Jicamarca. A few years later, *Hysell* [1996] and *Hysell and Woodman* [1997] produced images of plasma irregularities in equatorial spread *F* with higher definition by incorporating statistical inverse methods in the data inversion. The same basic algorithm has since been applied to studies of large-scale waves in the daytime and nighttime electrojet [*Hysell and Chau*, 2002; *Chau and Hysell*, 2004], bottom-type spread *F* layers [*Hysell et al.*, 2004a], quasiperiodic echoes from midlatitude sporadic *E* layers [*Hysell et al.*, 2002, 2004b], and the radar aurora [*Bahcivan et al.*, 2005]. Satisfactory performance of the original imaging algo-

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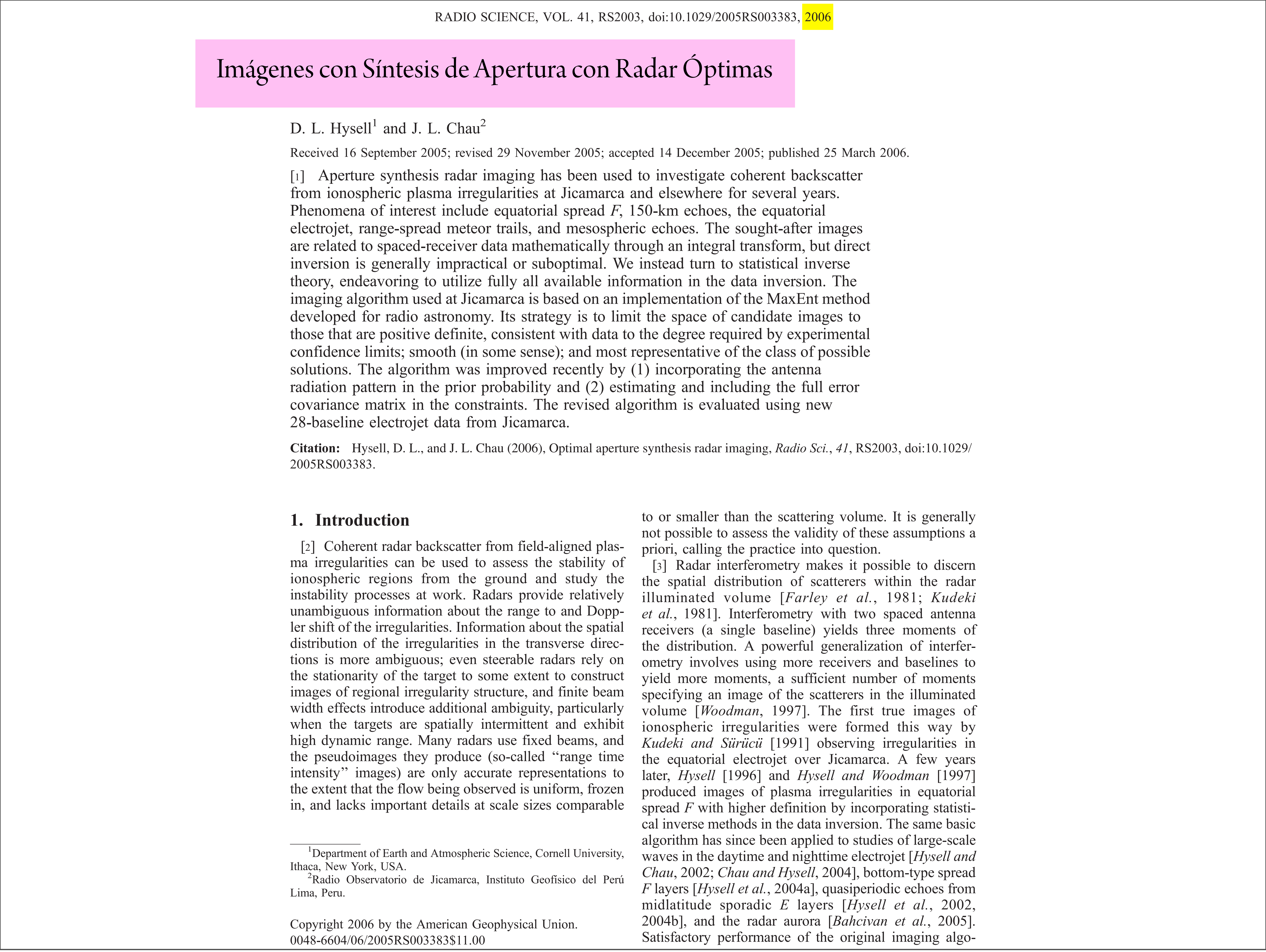
Imágenes con Síntesis de Apertura con Radar Óptimas



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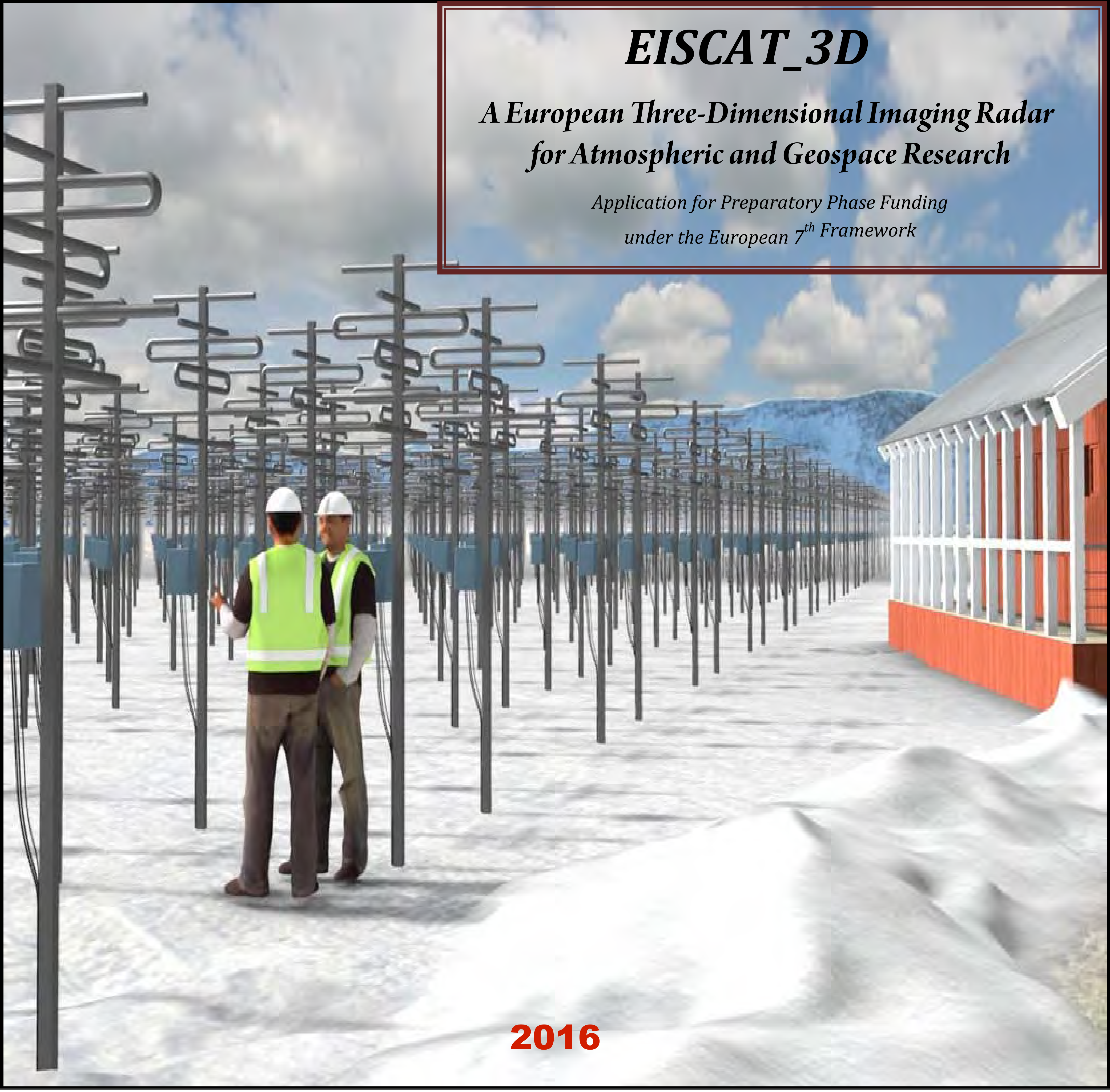
0048-6604/06/2005RS003383$11.00

Y todavía 45 años más tarde, en 2016 . . .



EISCAT_3D

A European Three-Dimensional Imaging Radar for Atmospheric and Geospace Research

Application for Preparatory Phase Funding
under the European 7th Framework

2016

The 3-Dimensional capability of the EISCAT_3D radars

C. La Hoz, V. Belyey and T. Grydeland
Tromsø, Norway

The built-in interferometric capabilities of the EISCAT_3D system, complemented with multiple beams and rapid beam scanning, is what will make the new radar truly three dimensional and justify its name. With the EISCAT_3D radars it will be possible to make investigations in 3-dimensions of several important phenomena such as Natural Enhanced Ion Acoustic Lines (NEIALs), Polar Mesospheric Summer and Winter Echoes (PMSE and PMWE), meteors, space debris, atmospheric waves and turbulence in the mesosphere, upper troposphere and possibly the lower stratosphere. Of particular interest and novelty is the measurement of the structure in electron density created by aurora. With scale sizes of the order of tens of meters, the imaging of these structures will be conditioned only by the signal to noise ratio which is expected to be high during some of these events since the electron density can be significantly enhanced. The electron density inhomogeneities and plasma structures excited by artificial ionospheric heating could conceivable be resolved by the radars provided that their variation during the integration time is not great.

Cesar.La.Hoz@uit.no

What could you do with an IS IMAGING radar?

- Electron density inside aurora
- NEIAL's
- PMSE, PMWE
- Plasma structures induced by Heating
- Meteors
- Space debris
- Atmospheric waves & turbulence:
  mesosphere, stratosphere, troposphere

3

Reprinted from JOURNAL OF ATMOSPHERIC SCIENCES, Vol. 31, No. 2, March 1974, pp. 493–505
American Meteorological Society
Printed in U. S. A.

1974

Radar Observations of Winds and Turbulence in the Stratosphere and Mesosphere

RONALD F. WOODMAN AND ALBERTO GUILLEN

Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima

(Manuscript received 16 August 1972, in revised form 19 September 1973)

ABSTRACT

A technique for the observation of radar echoes from stratospheric and mesospheric heights has been developed at the Jicamarca Radio Observatory. Signals are detected at the altitude ranges between 10–35 km and from 55–85 km with powers from many to several tens of decibels above noise level. The three most important frequency spectrum characteristics—power, Doppler shift and spectrum width—are observed in real time. The power levels as well as the spectral width are explained in terms of turbulent layers, with a thickness of the order of 100 m, in regions with a positive potential temperature or electron density vertical gradients. Continuous wind velocity records are obtained with a precision of the order of 0.02–0.2 m $\sec^{-1}$ for the vertical component and 0.20–2 m $\sec^{-1}$ for the horizontal, with a time resolution of the order of 1 min. The highest precisions are obtained at stratospheric heights. Fluctuations in velocity in the mesosphere are observed at the shortest gravity wave periods with amplitudes of the order of 1 m $\sec^{-1}$ for the vertical component and of 10 m $\sec^{-1}$ for the horizontal. Tidal components at these altitudes are not as large as predicted by theory. A technique to obtain the power, the Doppler shift, and the width of the frequency spectrum of the echo signals from only two points of the correlation function is described.

1. Introduction

Radar techniques have proved to be a very powerful tool for the study of the earth's upper and lower atmosphere. There are two relatively unconnected groups using powerful radars to study the earth's atmosphere. One of them, using the scattering properties of free electrons, has been studying the earth's ionosphere, the other, using the scattering property of water or ice particles and/or the fluctuations of index of refraction in clear air, has been dedicated to the study of meteorological phenomena in the troposphere.

Most of the work of the first group has been confined, either by interest or system capabilities, to the region between 90 and 10,000 km altitude, with special emphasis in the 200–700 km range [see Evans (1969) for a review]. The technique used is known in the literature as the "incoherent scatter" or "Thomson scatter" technique. Most of the important parameters that define the earth's ionosphere have been measured and studied this way. Several powerful radars have been designed and built for this purpose, among them the Jicamarca radar (11.95°S, 76.87°W) located near Lima, Peru, with which we are concerned in this paper.

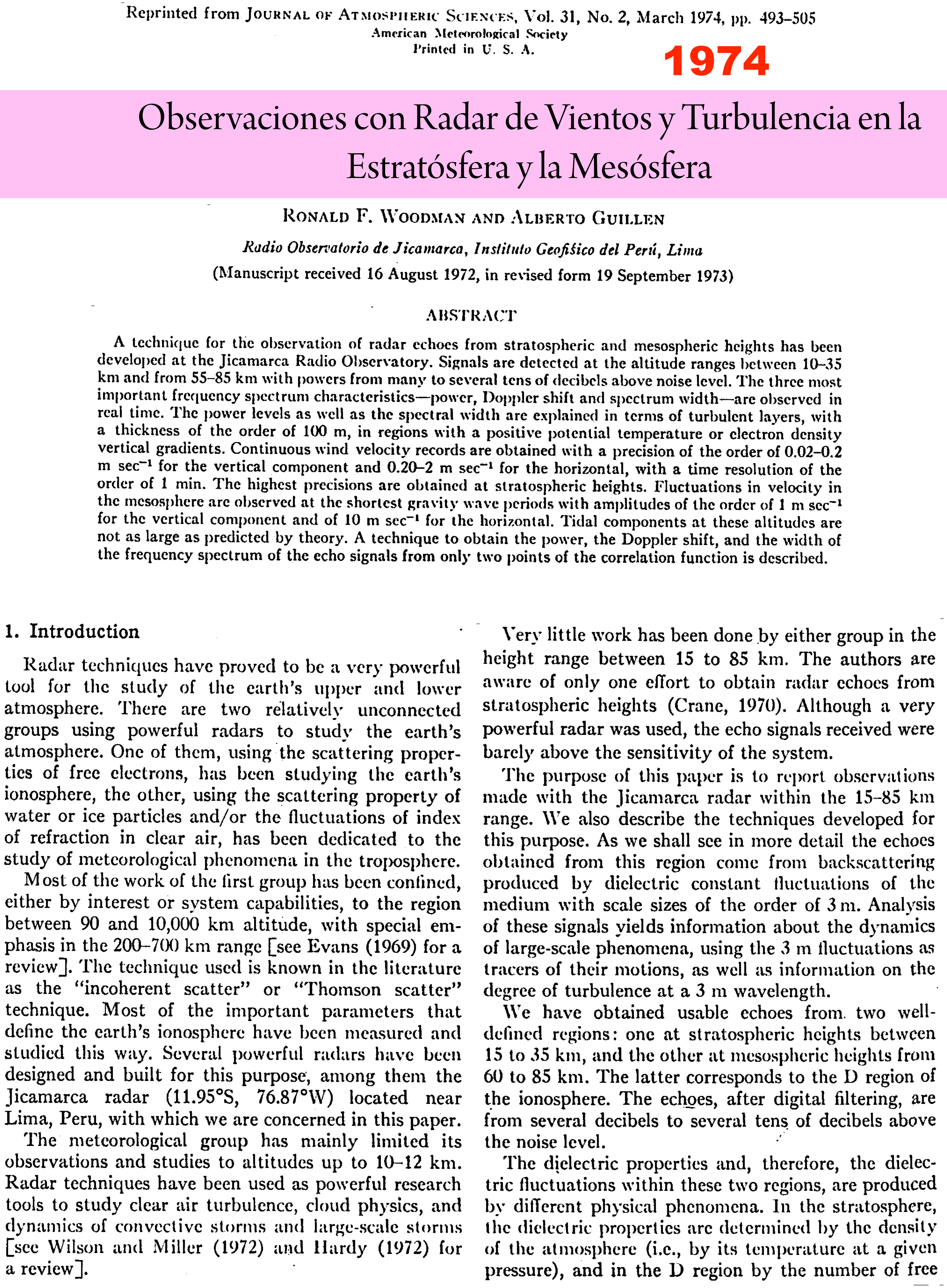
The meteorological group has mainly limited its observations and studies to altitudes up to 10–12 km. Radar techniques have been used as powerful research tools to study clear air turbulence, cloud physics, and dynamics of convective storms and large-scale storms [see Wilson and Miller (1972) and Hardy (1972) for a review].

Very little work has been done by either group in the height range between 15 to 85 km. The authors are aware of only one effort to obtain radar echoes from stratospheric heights (Crane, 1970). Although a very powerful radar was used, the echo signals received were barely above the sensitivity of the system.

The purpose of this paper is to report observations made with the Jicamarca radar within the 15–85 km range. We also describe the techniques developed for this purpose. As we shall see in more detail the echoes obtained from this region come from backscattering produced by dielectric constant fluctuations of the medium with scale sizes of the order of 3 m. Analysis of these signals yields information about the dynamics of large-scale phenomena, using the 3 m fluctuations as tracers of their motions, as well as information on the degree of turbulence at a 3 m wavelength.

We have obtained usable echoes from two well-defined regions: one at stratospheric heights between 15 to 35 km, and the other at mesospheric heights from 60 to 85 km. The latter corresponds to the D region of the ionosphere. The echoes, after digital filtering, are from several decibels to several tens of decibels above the noise level.

The dielectric properties and, therefore, the dielectric fluctuations within these two regions, are produced by different physical phenomena. In the stratosphere, the dielectric properties are determined by the density of the atmosphere (i.e., by its temperature at a given pressure), and in the D region by the number of free



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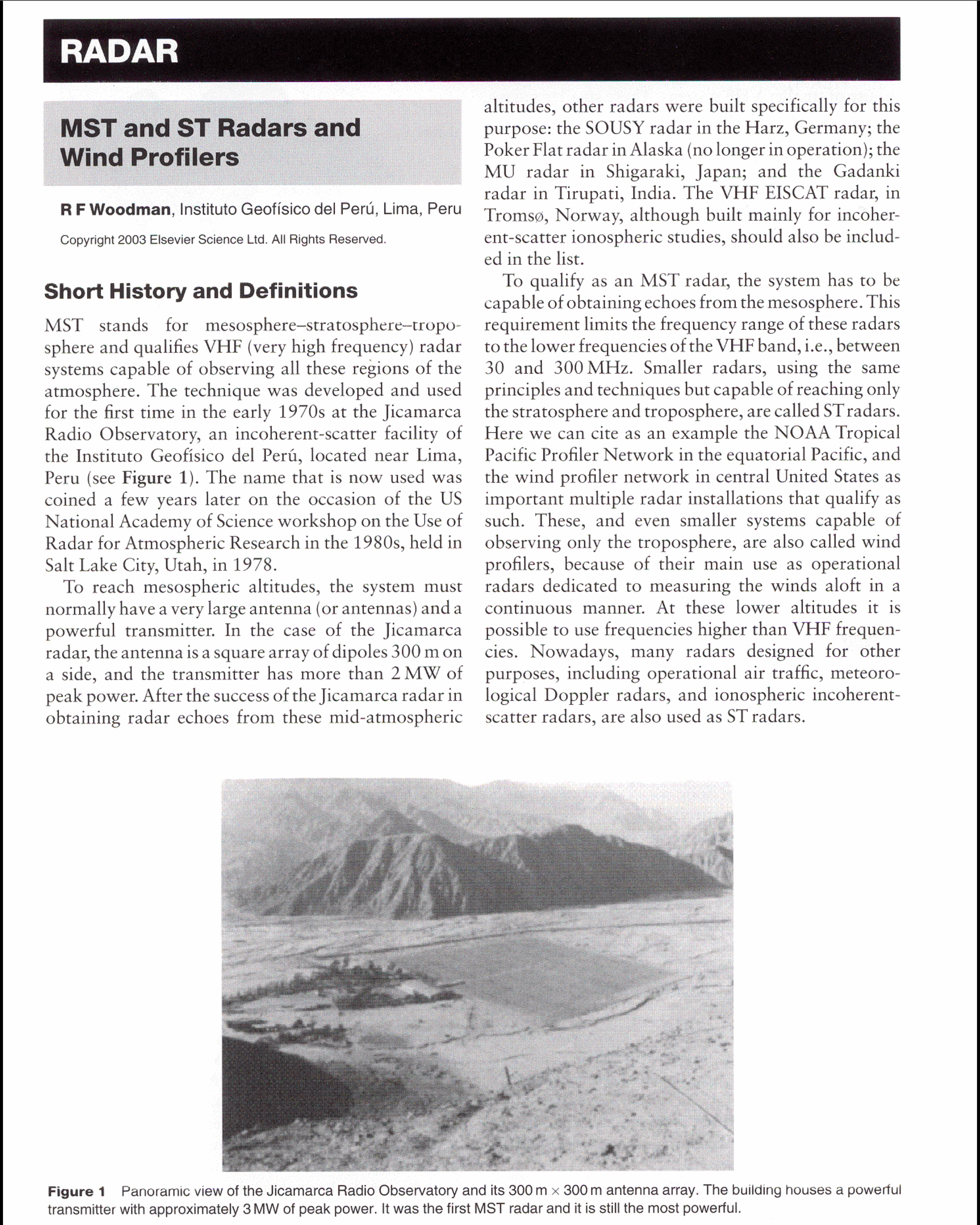

MST and ST Radars and Wind Profilers

R F Woodman, Instituto Geofísico del Perú, Lima, Peru

Short History and Definitions

MST stands for mesosphere–stratosphere–troposphere and qualifies VHF (very high frequency) radar systems capable of observing all these regions of the atmosphere. The technique was developed and used for the first time in the early 1970s at the Jicamarca Radio Observatory, an incoherent-scatter facility of the Instituto Geofísico del Perú, located near Lima, Peru (see **Figure 1**). The name that is now used was coined a few years later on the occasion of the US National Academy of Science workshop on the Use of Radar for Atmospheric Research in the 1980s, held in Salt Lake City, Utah, in 1978.

To reach mesospheric altitudes, the system must normally have a very large antenna (or antennas) and a powerful transmitter. In the case of the Jicamarca radar, the antenna is a square array of dipoles 300 m on a side, and the transmitter has more than 2 MW of peak power. After the success of the Jicamarca radar in obtaining radar echoes from these mid-atmospheric altitudes, other radars were built specifically for this purpose: the SOUSY radar in the Harz, Germany; the Poker Flat radar in Alaska (no longer in operation); the MU radar in Shigaraki, Japan; and the Gadanki radar in Tirupati, India. The VHF EISCAT radar, in Tromsø, Norway, although built mainly for incoherent-scatter ionospheric studies, should also be included in the list.

To qualify as an MST radar, the system has to be capable of obtaining echoes from the mesosphere. This requirement limits the frequency range of these radars to the lower frequencies of the VHF band, i.e., between 30 and 300 MHz. Smaller radars, using the same principles and techniques but capable of reaching only the stratosphere and troposphere, are called ST radars. Here we can cite as an example the NOAA Tropical Pacific Profiler Network in the equatorial Pacific, and the wind profiler network in central United States as important multiple radar installations that qualify as such. These, and even smaller systems capable of observing only the troposphere, are also called wind profilers, because of their main use as operational radars dedicated to measuring the winds aloft in a continuous manner. At these lower altitudes it is possible to use frequencies higher than VHF frequencies. Nowadays, many radars designed for other purposes, including operational air traffic, meteorological Doppler radars, and ionospheric incoherent-scatter radars, are also used as ST radars.

Figure 1 Panoramic view of the Jicamarca Radio Observatory and its 300 m × 300 m antenna array. The building houses a powerful transmitter with approximately 3 MW of peak power. It was the first MST radar and it is still the most powerful.

1999

Dr. R. Woodman receives the Appleton Prize

Presentation of the Appleton Prize

Professor A. David Olver, President of the UK Panel for URSI, presented the Appleton Prize as follows: The Appleton Prize is awarded to a distinguished scientist in the field of the Ionospheric Physics by the Council of the Royal Society on the recommendation of the Board of Officers of URSI. The prize commemorates the life and work of Sir Edward Appleton, who was a former president of the URSI. Sir Edward first demonstrated in 1924 the existence of the ionosphere by measuring the time of arrival of radio waves reflected by the layers of the ionosphere. His highly significant discoveries led to his being awarded the Nobel Prize in 1947 for his work in Ionospheric Physics and Radio Propagation. He worked on ionospheric propagation all his working life, even as he held increasingly distinguished posts. His contribution to URSI was immense where he valued interaction with radio scientists throughout the world. He once said, " the big things in science occur when an adventure takes place in the mind of an individual." Since the creation of the Appleton Prize, URSI has awarded it to distinguished scientists who fulfill Sir Edward's dream. This years' recipient, Professor Ronald F. Woodman fulfills this criteria well. He is an enormously creative scientist who has made major contributions to a wide range of topics related to radar probing of the upper atmosphere. He is one of the few scientists, active in South America, who has made major contributions to a wide range of topics related to radar probing of the upper atmosphere. He is one of the few scientists, active in South America, who has made major contributions to many areas of URSI interest, Professor Woodman was born in Peru and after graduating from the National University for Engineering went to the USA and obtained his PhD Degree from Harvard University on the subject of incoherent scatter. He then embarked on a distinguished career which has combined radio science with management of ionospheric and atmospheric research, notably Head of the Atmospheric Physics Group at the Arecibo Observatory and Director of the Jicamarca Observatory in Peru. He is now Executive President of the Institute of Geophysics in Peru. His major contributions included work on incoherent scatter, where he provided the first theory to explain exactly how ion-ion collisions affect the ion gyro-resonance. He pioneered and recently improved the measurement of plasma drift velocity in Peru to permit the better measurement of ionospheric studies. This technique and its more recent extensions to multi-radar imaging are widely used in studies of plasma instabilities at the equator and in the auroral zone. He also created the entire field of mesosphere, stratosphere, and troposphere wind profile measurements with VHF radars. A large network of wind profilers exists throughout the world because of his insights. His leadership of the radar ionospheric community has been exemplary and this makes him a worthy recipient of the Appleton Prize. The citation reads "*for major contributions and leadership in the radar studies of the ionospheric and neutral atmosphere*".

Radio Science Bulletin September 1999

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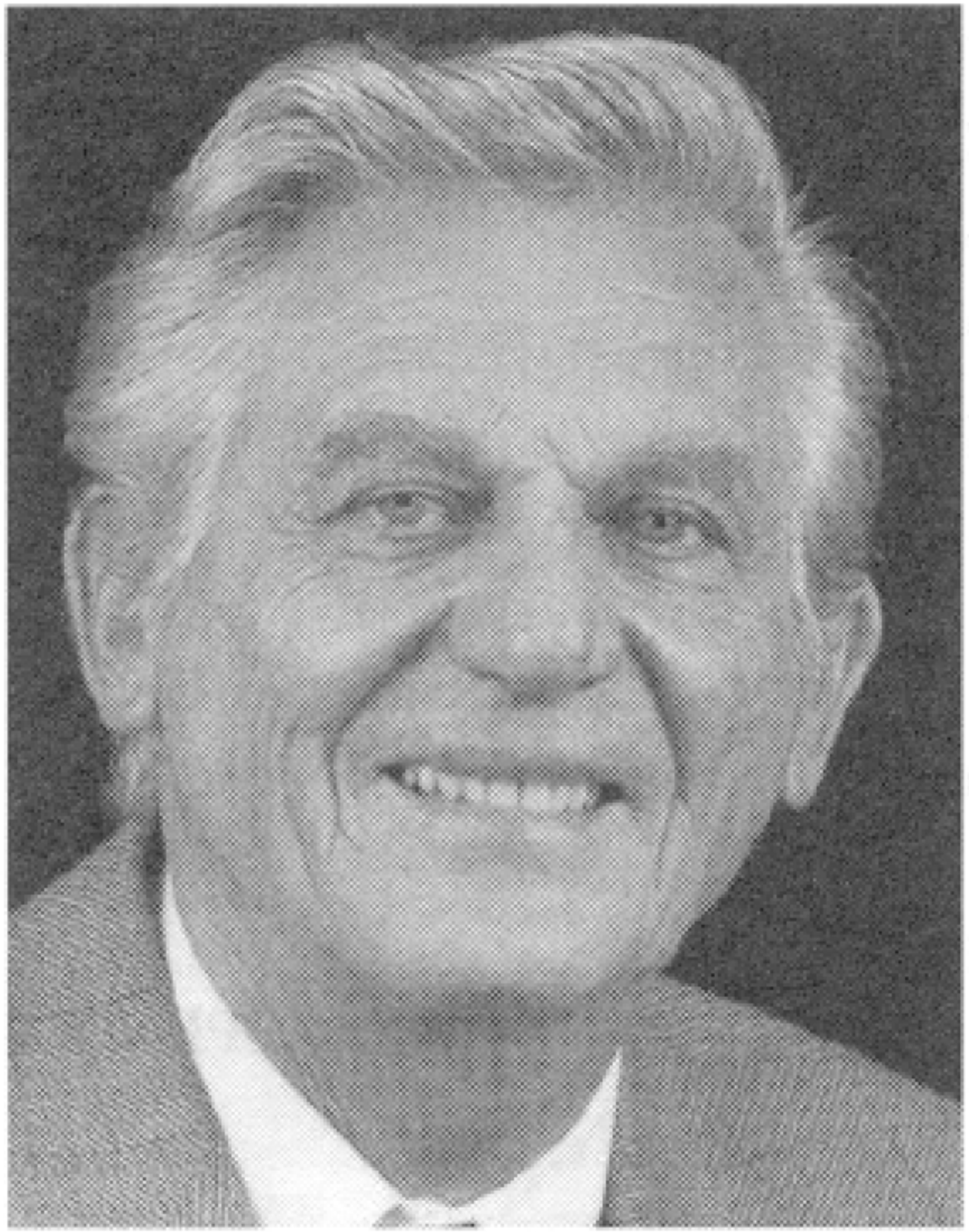
Él también creó un campo entero, el de las mediciones de perfil de vientos en la Mesósfera, la Estratósfera y la Mesósfera (MST) con radares de VHF. Una gran red de perfiladores existe hoy día a travez de todo el mundo debido a su creatividad.

Appleton Prize 1999

U.R.S.I.



4

1976

VOL. 81, NO. 31 JOURNAL OF GEOPHYSICAL RESEARCH NOVEMBER 1, 1976

Radar Observations of *F* Region Equatorial Irregularities

RONALD F. WOODMAN[1]

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CÉSAR LA HOZ[2]

Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima, Peru

Experimental results obtained with the Jicamarca radar and a new digital processing system during spread *F* conditions are presented. The data consist of two-dimensional maps showing backscatter power and samples of frequency spectra of the backscatter signals as a function of altitude and time. Almost simultaneous spread *F* backscatter power and incoherent scatter observations of electron density and vertical drifts are presented for one occasion. It is shown that spread *F* can occur at the bottomside, at the topside and the steep bottom of the *F* region, and in the valley between the *F* and *E* regions when the electric field is either positive, negative, or null. The existence of plumelike structures extending hundreds of kilometers in altitude and physically connecting the spread *F* on the topside with the bottomside is one of the highlights of the experimental results. They are interpreted as evidence of a Rayleigh-Taylor instability. A mechanism involving 'bubbles' or low-density plasma is proposed to extend the instability to the stable regions on the top. Other unstable processes are proposed for spread *F* at other altitude ranges. The frequency spectra show a large variety of shapes. Simple or multiple peak spectra from a few hertz to a few hundred hertz wide are found. An interpretation of the spectral shapes is presented in terms of turbulent motions and the angular extent of **k** vector angles of the fluctuation waves with respect to perpendicularity. A puzzling phenomenon, referred to as explosive spread *F*, which consists of the simultaneous onset of short time enhancements in the backscatter power and involves selected heights in an altitude range of the order of 100 km, is presented.

INTRODUCTION

There has been a recent renewed interest in the equatorial *F* region electron density irregularities, which for many years have been detected by the spread nature of the echoes that they produce on ionosondes. This phenomenon has been termed equatorial spread *F*. The renewed interest results both from a natural unsatisfied scientific curiosity and from new practical implications. The scientific interest can be understood by the fact that this phenomenon, although it has been observed for more than 35 years [*Booker and Wells*, 1938], is still poorly understood. From a practical point of view, communication and space applications engineers and scientists are finding out that satellite communications are not as reliable at equatorial latitudes as had been originally expected. VHF signals emitted by satellites and received by ground-based equatorial region stations become almost useless during the occurrence of this phenomenon, since the irregularities produce deep and frequent fading (scintillations) of the signals. Strong effects are observed even at microwave frequencies; this presents some annoying problems to the designers and users of satellite communication, navigation, and geodetic systems.

It is not our intention to review here either the large amount of work on *F* region irregularities or the different techniques used to date for their study, since that would result in a very large review paper in itself. It will be sufficient for our purpose to enumerate very briefly the different techniques and to mention some of the most important conclusions derived from them.

A list of the more important techniques would include conventional ionosondes, topside ionosondes, in situ satellite probes, and propagation of satellite beacons (phase and amplitude scintillation). Ionosondes and satellite scintillations have been used mainly to obtain statistical data regarding temporal and spatial (latitude and longitude) spread *F* behavior and its relationship to other geophysical phenomena (e.g., magnetic and solar activity). *Freemouw and Rino* [1971] have collected the satellite scintillation observations into an empirical mathematical model. Ionosonde observations have been reviewed by *Skinner and Kelleher* [1971]. Most of the results reported in the literature have made use of these techniques. That these techniques are limited is shown by the fact that despite the long and intensive effort to find a theoretical explanation for the physical nature of the phenomenon, this effort has been unsuccessful.

Satellite in situ probes are powerful instruments, but they have been only recently used to study the irregularities in a systematic way [*Dyson*, 1969; *Kelley and Mozer*, 1972; *McClure and Hanson*, 1973; *Dyson et al.*, 1974]. Although they are capable of observing many perturbed as well as background properties, they have also failed to produce experimental evidence for a generally accepted theory that would explain the physical process responsible for the formation of the equatorial *F* region irregularities. The limitations of satellite probes come from the inability of the instruments to observe either the irregularities and the background ionospheric properties in the dimensions transverse to the satellite path, or their development as a function of time.

Recently, special instrumental rockets have been flown to study spread *F* irregularities (M. C. Kelley, private communication, 1975; F. A. Morse, private communication, 1975).

1976

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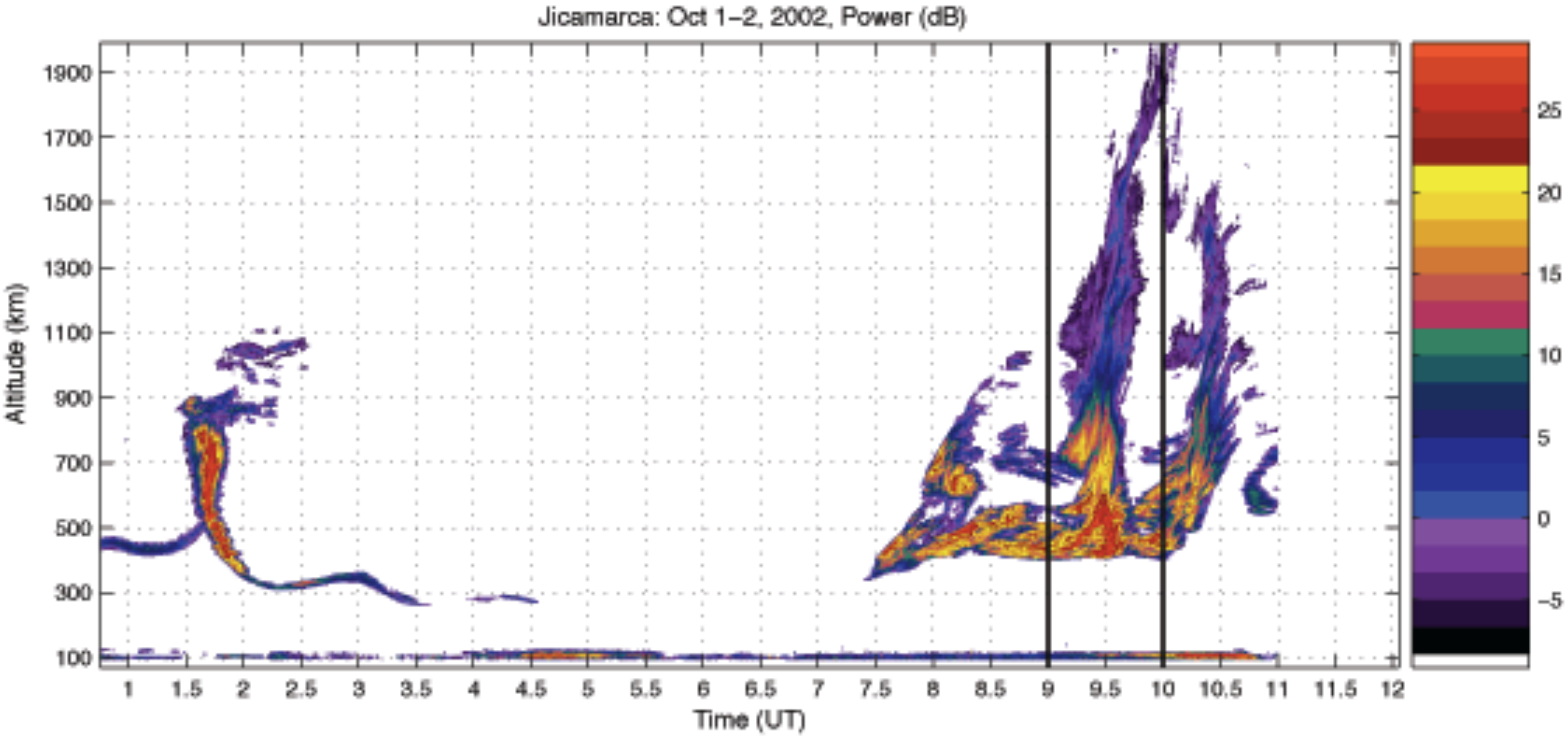

Nicolls, M.J., M.C. Kelley, A.J. Coster, S.A. González, and J.J. Makela, Imaging the structure of a large-scale TID using ISR and TEC data, Geophys. Res. Lett., 31, 2004.

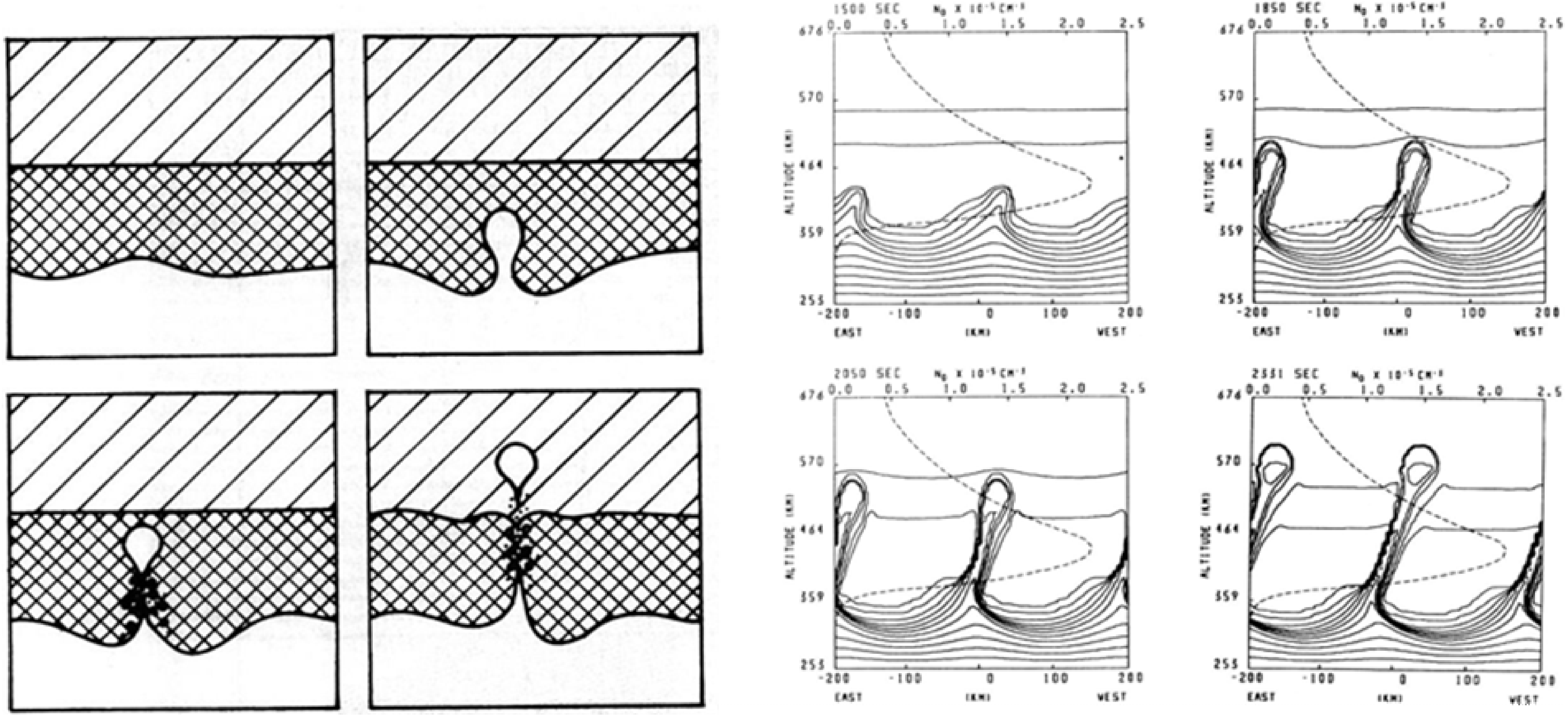

Fig. 8. The left panel shows a Woodman and La Hoz (1976) sketch of how a low density bubble propagates to the stable top provided that the densities there are higher than those in the lower third. The right panel shows the result of a computer simulation by Zalesak et al. (1982) of the same. The westward tilt reproduces the tilt of the plumes and is produced by a eastward neutral wind, also in accord with the Woodman and La Hoz (1976) explanation.

introductions). The idea of a bubble "floating" to the top was first presented by Woodman at the 1975 Gordon Conference on Space Plasma Physics where it was suggested that that name. The name comes from the fact that density fluctuations in a plasma, being incompressible in the plane transverse to the magnetic field, can come about only by transport-

33 años más tarde, en 2009 . . .

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y después de miles de artículos provenientes
de todo el mundo . . .

Ann. Geophys., 27, 1915–1934, 2009
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Annales Geophysicae

Spread F – an old equatorial aeronomy problem finally resolved?

R. F. Woodman

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Received: 28 October 2008 – Revised: 25 March 2009 – Accepted: 27 March 2009 – Published: 4 May 2009

Abstract. One of the oldest scientific topics in Equatorial Aeronomy is related to Spread-F. It includes all our efforts to understand the physical mechanisms responsible for the existence of ionospheric F-region irregularities, the spread of the traces in a night-time equatorial ionogram – hence its name – and all other manifestations of the same. It was observed for the first time as an abnormal ionogram in Huancayo, about 70 years ago. But only recently are we coming to understand the physical mechanisms responsible for its occurrence and its capricious day to day variability. Several additional techniques have been used to reveal the spatial and temporal characteristics of the F-region irregularities responsible for the phenomenon. Among them we have, in chronological order, radio star scintillations, trans-equatorial radio propagation, satellite scintillations, radar backscatter, satellite and rocket in situ measurements, airglow, total electron content techniques using the propagation of satellite radio signals and, recently, radar imaging techniques. Theoretical efforts are as old as the observations. Nevertheless, 32 years after their discovery, Jicamarca radar observations showed that none of the theories that had been put forward could explain them completely. The observations showed that irregularities were detected at altitudes that were stable according to the mechanisms proposed. A breakthrough came a few years later, again from Jicamarca, by showing that some of the "stable" regions had become unstable by the non-linear propagation of the irregularities from the unstable to the stable region of the ionosphere in the form of bubbles of low density plasma. A problem remained, however; the primary instability mechanism proposed, an extended (generalized) Rayleigh-Taylor instability, was too slow to explain the rapid development seen by the observations. Gravity waves in the neutral background have been proposed as a seeding mechanism to form irregularities from which the instability would grow, but the former are difficult to observe as a controlling parameter. Their actual role still needs to be determined. More recently, radar observations again have shown the existence of horizontal plasma drift velocities counter streaming the neutral wind at the steep bottom of the F-region which produces a fast growing instability from which a generalized Rayleigh-Taylor instability can grow. The mechanisms proposed would explain the rapid development of the large and medium scale irregularities that have been observed, including some seen only by radars. Nevertheless, a proper quantitative theoretical mechanism that would explain how these irregularities break into the very important meter scale ones, responsible for the radar echoes, needs to be developed. This paper makes a selective historical review of the observations and proposed theories since the phenomenon was discovered to our current understanding.

Keywords. Ionosphere (Equatorial ionosphere; Ionospheric irregularities) – Space plasma physics (Waves and instabilities)

1 Introduction

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La F-dispersa – ¿un problema de aeronomía antiguo finalmente resuelto?

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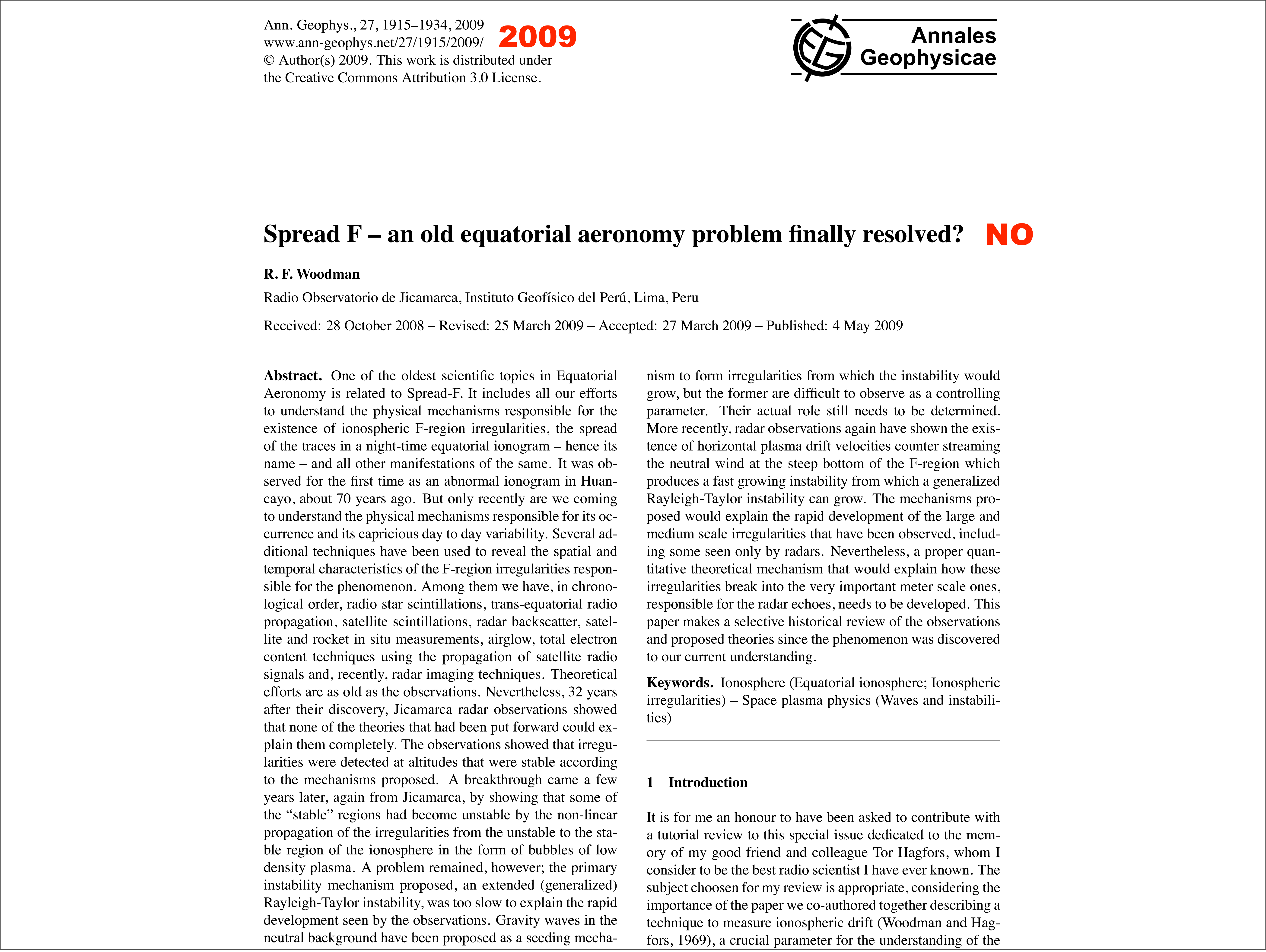

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A good theory in physics should be able to make good predictions, and we are not in that position yet.

R. F. Woodman, 2009

Una buena teoría de física debería tener la capacidad de hacer buenas predicciones, pero no estamos en esa posición todavía.

R. F. Woodman, 2009

Los 4 Pilares ++

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EPÍLOGO

PROVISIONAL

La producción científica de R.F. Woodman se caracteriza por tener colas muy largas con bifurcaciones inesperadas que todavía no terminan.

☺

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Woodman ha contribuido más que ningún peruano a elevar al Perú a los más altos de la investigación mundial en el campo de ciencias del espacio.

☺

Excerpt from R. Woodman's PhD Thesis, 1967

Transcription from the original pages 3-4

Despite the extensive amount of theoretical work on the problem of incoherent scattering, this is still not complete. In the sense that, with the exception of two papers, one by Farley[5] and the other by Dougherty[6] which we shall briefly discuss, no one has included the effect of ion-ion interactions or so-called Coulomb collisions. Ionospheric plasmas, even in their most dense regions (F_{max} peak) have an affective ion-ion collision frequency of the order of 10 sec^{-1}, which is small compared with to other characteristic frequencies like the ion gyro-frequency and the thermal characteristic frequency (inverse of the time it takes an ion to travel one wavelength). These frequencies are of the order of 160 and 2000 radians/second (for $\lambda = 1.5$ meters) respectively. Thus, initially it appeared that neglecting the effect of this type of collision was justified. A more careful analysis shows that this is not the case, especially in predicting the effects of the magnetic field and ion gyro-resonance phenomena. A more careful analysis was stimulated by the fact that $[O]^+$ ion-gyro-resonances predicted by the collisionless model were not observed experimentally.

In the paper by Farley[5] mentioned above, he *estimated* the amount of probabilistic diffusion that any ion suffers after a gyro-period when subject to Coulomb collisions. From this he concluded, as we shall also see, that the effect of Coulomb collisions is indeed important and responsible for the failure of the experimental observations of oxygen gyro-resonances.

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