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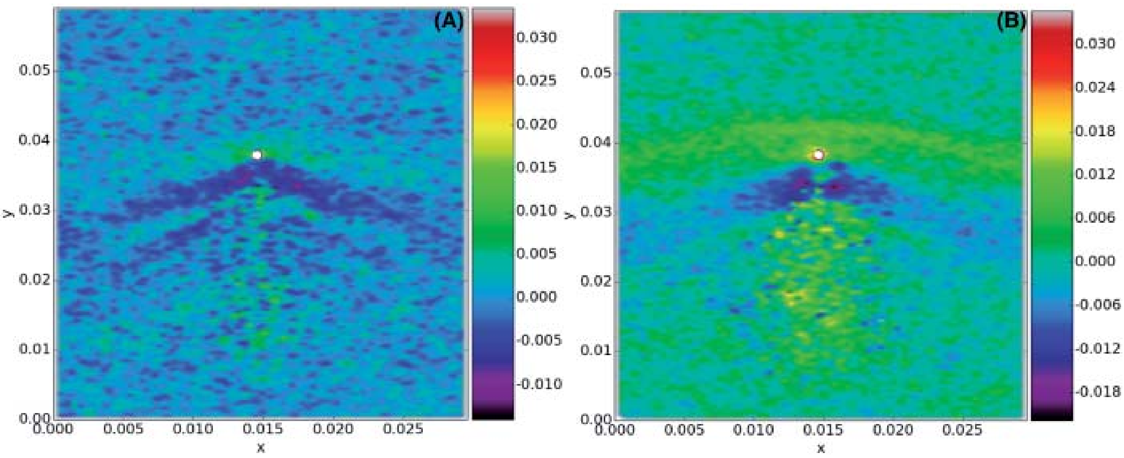

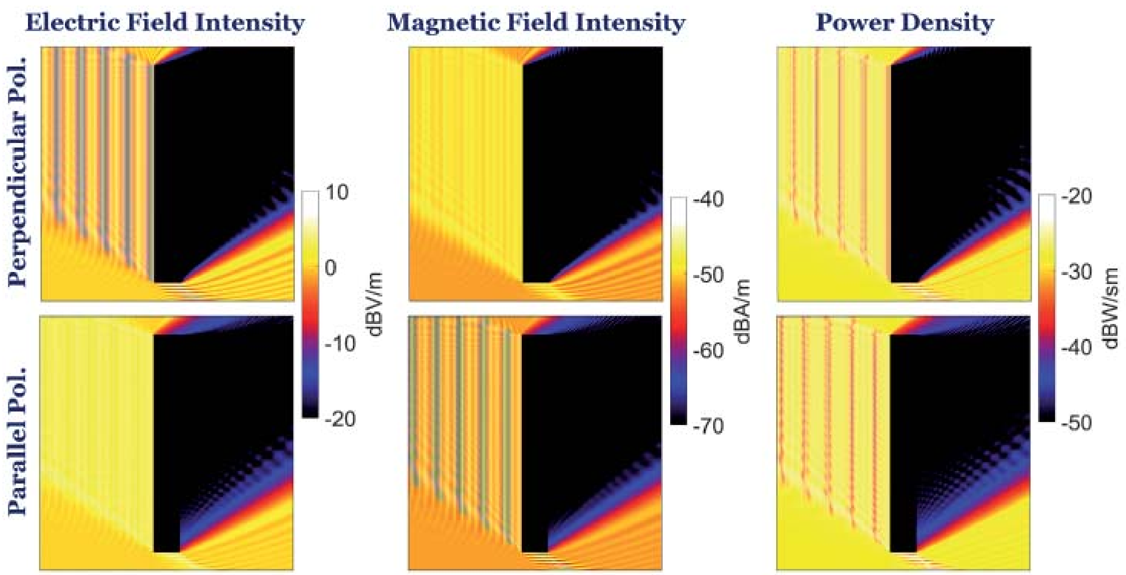

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Contents

Cover: (top) The formation of a Mach cone for a charged projectile in a dusty plasma where the charge on the projectile was the same as the charge on the dust particles, streaming with a Mach number of $M \approx 1.1$*. (B) When the projectile charge was increased to 10 times the charge on the dust particles, nonlinear precursor pulses were excited in the fore-wake region. The white disc symbol marks the position of the projectile particle. The simulation parameters were as given in the text. See Figure 7 and the text associated with it in the paper by Abhijit Sen. (bottom) The electric-field intensity, magnetic-field intensity, and power-density distributions obtained for the perfectly electrically conducting rectangular box of SOLBOX-18 when it was illuminated by plane waves with oblique incidences at 64 GHz. The maximum dimension of the box was* 64λ*, and the waves traveled from left to right. See the SOLBOX column by Özgür Eriş, Şirin Yazar, and Özgür Ergül.*

The International Union of Radio Science (URSI) is a foundation Union (1919) of the International Council of Scientific Unions as direct and immediate successor of the Commission Internationale de Télégraphie Sans Fil which dates from 1914.

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Second Special Issue on URSI AP-RASC 2019

This issue is the second of two special issues of the *Radio Science Bulletin* with papers based on presentations from the 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC 2019), held March 10-14, 2019, at the India Habitat Centre, New Delhi, India (the first special issue was September, 2020). This issue contains one of the General Lectures, the keynote presentations from Commissions G and H, and a paper based on one of the Student Paper Competition papers. We also have one regular, non-special-issue paper.

We are grateful to Amitava Sen Gupta, Subra Ananthakrishnan, and Kazuya Kobayashi, the guest editors of these special issues, for all of their excellent efforts in bringing these papers to us. They provided a separate introduction to the special issues in the September issue.

While all of these papers are based on presentations at AP-RASC 2019, they all were invited on the basis of being significantly extended beyond the conference papers.

In his paper based on his AP-RASC 2019 General Lecture, Yoshiharu Omura provides a summary of the work of his group in recent years on nonlinear wave-particle interactions related to the dynamics of the Earth's outer radiation belt. The main results explained include how whistler-mode rising-tone chorus emissions lead to nonlinear wave trapping. This in turn causes a rapid formation of the relativistic electron flux. Nonlinear interaction with electromagnetic ion-cyclotron rising-tone emissions results in pitch-angle scattering, which precipitates the relativistic electron flux in the outer radiation belt. This paper is a nice follow-on to a previous summary published in the *Radio Science Bulletin*.

The Commission G keynote paper by Archana Bhattacharyya looks at the challenges of predicting low-latitude ionospheric scintillations. The paper reviews current and recent past approaches to this prediction problem, noting that most have been based primarily on models involving the linear growth rate of the Rayleigh-Taylor instability. The limitations of such models are explained. The need for high-resolution three-dimensional models of equatorial plasma bubble development under different background conditions is identified, and examples of what can be obtained where such models are available are given.

Abhijit Sen's Commission H keynote paper deals with the nonlinear precursor waves found in front of an object moving at supersonic speed in a plasma. Such waves are relevant to understanding how the solar wind interacts with the Earth and the moon. They also may be useful in helping to detect charged debris in the ionosphere. This paper describes the nature and properties of such waves as determined through laboratory experiments and a variety of simulations. How these results may be applied to a substantial range of problems is explored.

In their Student Paper Competition paper, Sreenath Reddy Thummaluru and Raghvendra Kumar Chaudhary look at how the radar cross section (RCS) of a multiple-input multiple-output (MIMO) antenna can be reduced. Their approach was to replace the ground plane of the MIMO antenna with a frequency-selective-surface array that was insensitive to angle of incidence. The method presented for carrying out the design is at least as interesting and important as the resulting design itself.

In their paper not associated with the special issue, S. Y. Polevoy, A. S. Vakula, S. V. Nedukh, and S. I. Tarapov describe a non-contact method for identifying liquids in closed containers. Specifically, the use of two oppositely connected planar photonic crystals excited at microwave frequencies in a geometry where the liquid perturbed the resonance properties of the planar photonic crystals was explored. It was shown that a variety of liquids in thin containers such as plastic bottles could be identified. The effects of many important parameters on the identification process were measured and/or simulated and are explored in the paper.

Our Other Contributions

Tayfun Akgul has brought us a new perspectives on bank robbery in his Et Cetera column. I think you will enjoy them.

Amy Shockley and Randy Haupt bring us the second in their series on the ethical setting of priorities. I suggest you make reading it a priority.

In Giuseppe Pelosi's Historical Corner, Stefano Selleri looks at the history of the Clausius-Mossotti and the Lorentz-Lorenz relations. These relations, deal with fact that the ratio of two polynomials in either the permittivity or the index of refraction of a medium is a constant for a particular medium. The history of these relations involves at least four scientists, and even has controversy surrounding what name should be given to the relations.

Sadly, we have In Memoriam pieces for five very respected radio scientists in this issue: Peter Clarricoats, Iwane Kimura, Alan Rodger, Roberto Sorrentino, and Valerian Tatarskii.

Özgür Ergül's Solution Box column presents an interesting study by Özgür Eriş, Şirin Yazar, and Özgür Ergül of electromagnetic scattering by a deceptively simple geometry: a rectangular perfectly electrically conducting box. However, the box is electromagnetically quite large at the wavelengths in question, and it is desired to understand in some detail the electromagnetic fields in the very near field of the box. That results in a computationally challenging problem with some fascinating results.

In his Telecommunications Health and Safety column, Jim Lin takes a critical look at the US FCC's recent action regarding radiation safety for 5G wireless communications. Specifically, he examines why no changes were made in the current safety limits, and what are some of the implications of that decision.

Asta Pellinen Wannberg has brought us many very interesting contributions from contemporary women radio scientists around the world in her Women in Radio Science column. In this issue, she has the biography of Elizabeth Alexander as given by Dr. Alexander's daughter, Mary Harris. Dr. Alexander's quite significant contributions in two totally disjoint fields spanned a relatively short career, from the mid-1930s through the late 1950s. I think you'll enjoy reading this contribution, and there is a complete book available if you have further interest.

URSI GASS 2020 and 2021

Because of the coronavirus, the face-to-face version of the 2020 URSI General Assembly and Scientific Symposium has been postponed until August 7-14, 2021, in Rome, Italy. However, those who have had papers accepted for presentation at URSI GASS 2020 have several options for presenting them as part of a virtual conference in August 2020. Authors should have received an e-mail explaining the options by now. Additional information will be available on the symposium Web site: www.URSI2020.org. This will soon also include information on how to register to view the papers for the virtual GASS 2020, and how to participate in several live online events associated with GASS 2020.

The Atlantic Radio Science Conference (AT-RASC) will be held in Gran Canaria, Spain, May 30-June 4, 2022, and the Asia-Pacific Radio Science Conference (AP-RASC) will be held in Sydney, Australia, August 20-25, 2022. Yes, both AT-RASC and AP-RASC will be held in the same year for 2022, only. The URSI GASS will again be held in Sapporo, Japan, August 19-26, 2023, and thereafter the normal URSI triennial schedule of flagship meetings will be restored.

I hope this issue of the *Radio Science Bulletin* finds you, your family, and colleagues well in this time of coronavirus pandemic. Please stay safe.

Ross

Nonlinear Wave-Particle Interactions in the Earth's Inner Magnetosphere: Dynamic Variation of the Earth's Outer Radiation Belt Due to Whistler-Mode Chorus and EMIC Waves

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This invited paper is based on the General Lecture presented at the URSI Asia-Pacific Radio Science Conference (AP-RASC), New Delhi, India, March 2019

Abstract

Since publication of our previous summary paper on nonlinear wave-particle interactions, published in the *Radio Science Bulletin* [1], we have achieved a number of advances in the study on the variation of the Earth's outer radiation belt. This paper summarizes our updated understanding of the dynamics of radiation-belt electrons (MeV) interacting with whistler-mode chorus emissions and electromagnetic ion-cyclotron (EMIC) waves, generated through nonlinear interactions with energetic electrons and protons (10-100 keV) injected from the magnetotail at the time of magnetic disturbances. This paper is not a review paper comprehensively covering all important papers of the topics, but it is a summary of recent papers from our research group on nonlinear wave-particle interactions related to the dynamics of the radiation belt. The major results are that rapid formation of the relativistic electron flux takes place through acceleration due to nonlinear wave trapping by whistler-mode rising-tone chorus emissions. A substantial amount of relativistic electron flux in the outer radiation belt is precipitated through pitch-angle scattering due to nonlinear interaction with EMIC rising-tone emissions.

1. Generation of Whistler-Mode Chorus Emissions

Whistler-mode waves are one of the most dominant plasma waves in the geospace environment. These waves are generated from two different regions of the magnetosphere. One is the atmosphere, where lightning occurs, generating electromagnetic waves of a wide frequency range. Some low frequency part of the waves propagate as whistlers along the magnetic-field lines to the ground in the other hemisphere, with a characteristic frequency variation due to the dispersion effect of the magnetospheric plasma. The other region of wave generation is the magnetic equator, where energetic electrons are injected from the magnetotail at the time of geomagnetic disturbances. In the process of the transportation to the inner magnetosphere, the energetic electrons develop temperature anisotropy, generating whistler-mode waves from the thermal fluctuations.

A whistler mode wave with the maximum linear growth rate due to anisotropic energetic electrons grows at the wave-normal angle parallel to the background magnetic field. Once the growing wave amplitude attains a threshold amplitude, the wave packet grows through the nonlinear wave growth process due to formation of an electromagnetic electron hole in the velocity phase space [2, 3]. The electron hole is formed because of the incoming resonant electrons passing around the wave's potential without being trapped into the potential. The center of the wave's potential is a stable equilibrium point for a trapped particle satisfying the second-order resonance condition. The electron hole results in a resonant current, $\mathbf{J}_B$, in the direction of the wave's magnetic field, modifying the cold-plasma dispersion relation, inducing the faster wave phase variation in time, i.e., the higher wave frequency. Because of the positive frequency-sweep rate, the inhomogeneity factor, *S*, becomes nonzero, making the wave's potential asymmetric in gyrophase relative to the wave's magnetic field. The untrapped resonant electrons, which have not been affected by the foregoing wave packets, can traverse the resonance velocity at limited gyrophase, resulting in the resonant current in the parallel direction of the wave's electric field, i.e., $J_E(<0)$, which causes wave growth. The wave grows at a higher frequency forming a new wave packet separated from the triggering wave. The wave growth is an absolute instability occurring at the equator above the threshold wave amplitude [4]. The wave grows up to an optimum wave amplitude [5]. The wave growth induced by the resonant current is due to a nonlinear gyrophase modulation that depends on the wave amplitude. The growth rate is inversely proportional to a square root of the wave amplitude. The optimum wave-growth condition cannot be maintained above the optimum wave amplitude because of the diminishing growth rate. After reaching the optimum amplitude, the amplitude gradually decreases, forming a finite wave packet called a subpacket.

The subpacket generated at the equator propagates along the ambient magnetic field. Since the wave is coherent, counter-streaming energetic electrons interact with the wave packet to form an asymmetric electron hole with the inhomogeneity factor S ($|S|<1$) due to the gradient of the magnetic field. The asymmetric electron hole generates a negative J_E, resulting in the convective nonlinear wave growth. The energetic electrons go through the resonance with the wave, giving energy to the wave, and they are organized in gyrophase with a wavenumber corresponding to the new frequency of the wave packet generated at the equator. Even after passing through the wave packet, the gyrophase structure in the group of energetic electrons is kept for a while, being able to transmit a new triggering wave with the new frequency.

The exact process of the wave generation from the phase-organized energetic electrons is yet to be clarified in future studies. The newly generated waves with the increased frequency works as a new triggering wave for the next cycle of an electron hole generation near the equator. The triggering process of frequency increase is repeated to make the wave's frequency gradually increase to form a discrete rising-tone emission, as found in spacecraft observations [6] and as shown in Figure 1. The generation of subpackets with rising-tone frequencies can take place near the equator when a triggering wave has an amplitude greater than the threshold wave amplitude. The nonlinear process of wave generation has been confirmed for EMIC waves by a hybrid code simulation [7].

2. Long Time Modeling of Radiation Belts by Numerical Green's Function Method

Chorus emissions are coherent waves, being capable of accelerating 10 keV to 100 keV electrons to several MeV energies very efficiently by nonlinear trapping processes called relativistic turning acceleration (RTA) [8] and

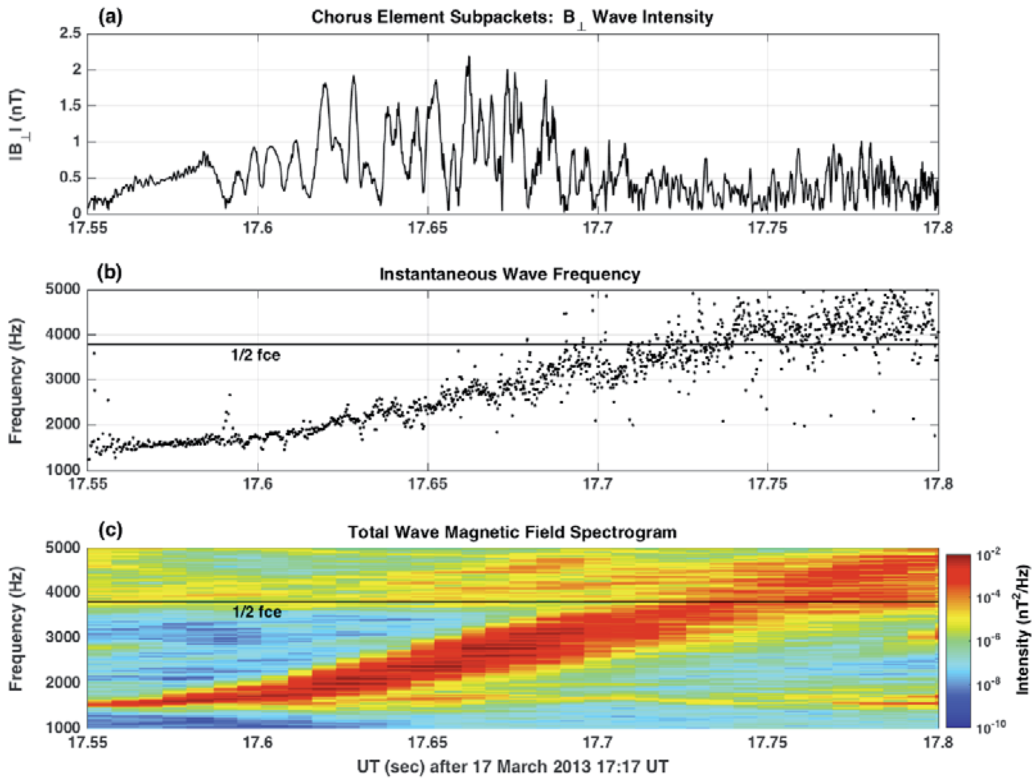

Figure 1. A subpacket analysis of a whistler-mode chorus emission observed by RBSP A. (a) The magnitude of the wave's magnetic field. (b) The instantaneous wave frequency. (c) The spectrogram of the total wave's magnetic field (after Foster et al. [6]).

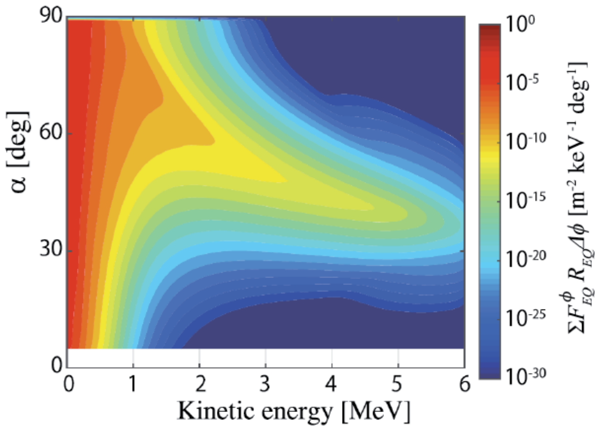

Figure 2. The equatorial electron distribution function after 500 times interactions with chorus elements (after Kubota and Omura [11]).

ultra-relativistic acceleration (URA) [9]. The nonlinear trapping occurs for resonant electrons with a limited range of gyrophase angle and specific timing of encountering with a wave packet. The trajectories of trapped electrons follow the resonance velocity of the wave, while the untapped electrons undergo adiabatic motion after strong modification of orbit at the resonance. The evolution of the velocity distribution function cannot be described by a diffusion equation, while solving diffusion equations using quasi-linear modeling has been used in modeling of the radiation belts as a coarse approximation. It only takes into account the first-order resonance condition, neglecting the nonlinear trapping effect of the second-order resonance condition. We have developed a new method of modeling the rapid formation of the radiation belt by using the concept of Green's functions, as described below.

Assuming a pair of specific chorus elements is propagating northward and southward from the equator, we performed a series of test particle simulations, calculating trajectories of a large number of energetic electrons with the same kinetic energy and equatorial pitch angle, and with different gyrophases and different positions along the magnetic field line. These particles formed a delta-function in the velocity phase space of kinetic energy and equatorial pitch angle. From the test-particle simulation, we could find how the delta-function was modified after the interaction with a pair of the chorus elements. The velocity distribution function in the phase space after the interaction is a kind of Green's function that is a solution to the source term specified by a delta function. We obtained a set of numerical Green's functions for different delta functions with energies from 0.01 MeV to 6 MeV with an interval of 0.01 MeV and equatorial pitch angles from 5° to 90° with an interval of 1°.

As a model, we next assumed a continuous injection of energetic electrons in the equatorial region of the inner magnetosphere with a uniform distribution over an energy range of 10 keV to 30 keV and an equatorial pitch-angle range of 5° to 90°. We were able to obtain the evolution of the distribution function of the injected electrons by numerically taking the convolution integral with the Green's functions. We also assumed that the same chorus elements were repeatedly generated at the equator with certain intervals, typically 0.5 - 1 second. By repeatedly taking the convolution integral of the evolving distribution with the Green's functions, we could trace longtime evolution of the energetic electrons accelerated to MeV energies [10].

More-realistic modeling of the outer radiation belt was implemented by assuming a localized generation region of chorus emissions in a certain range of longitude [11]. As the energy of trapped electrons increases, the eastward drift velocity of the electrons also increases. We added a longitude as another variable of the Green's functions. When the generation region is localized, the acceleration of the relativistic electrons stops because the relativistic electrons drift away from the generation region and go around the Earth. After one rotation around the Earth, the relativistic electrons again enter the generation region, and they are accelerated further, to higher energies of several MeV. Since highly relativistic electrons reenter the generation region faster than lower-energy electrons because of the larger drift velocity, we found an enhanced relativistic electron flux spreading wider in pitch angle, as shown in Figure 2. In comparison with the case of the uniform distribution of the source region, the time scale of the acceleration by chorus emissions became longer than a few minutes. In the case of the source region distributed over a longitudinal range of 30°, it took about one hour to build a sufficiently large flux of MeV electrons as the outer radiation belt [6].

3. Oblique Chorus-Electron Interactions

A wave packet of a chorus element generated near the equator propagates along the magnetic field. In the process of propagation, the wave-normal angle gradually increases because of the curvature of the dipole magnetic field. With a nonzero perpendicular wave number, $k_\perp$ energetic electrons with large perpendicular velocities can get into cyclotron resonance at multiple harmonics of the cyclotron frequency. The resonance condition is expressed by $\omega - k_\parallel v_\parallel = n\Omega_c$, where Ω_c is the cyclotron frequency. The nonlinear wave-particle interactions take place with different n as shown in Figure 3. Figure 3a shows some trajectories of 2 MeV electrons in the $z - v_\parallel$ plane. The dashed lines indicate the resonance velocities with $n = -1$, 0, 1, 2, while Figure 3b shows the Green's function. Averaging the cyclotron motion around the guiding center, we obtained the generalized equations of nonlinear particle trapping with the nth resonance [12]. The validity of the nonlinear equations was confirmed by test-particle simulations [13, 14]. Effective acceleration of MeV electrons by nonlinear trapping through Landau resonance ($n = 0$) takes place. It is rather surprising that the acceleration is due to the perpendicular component of the electric wave

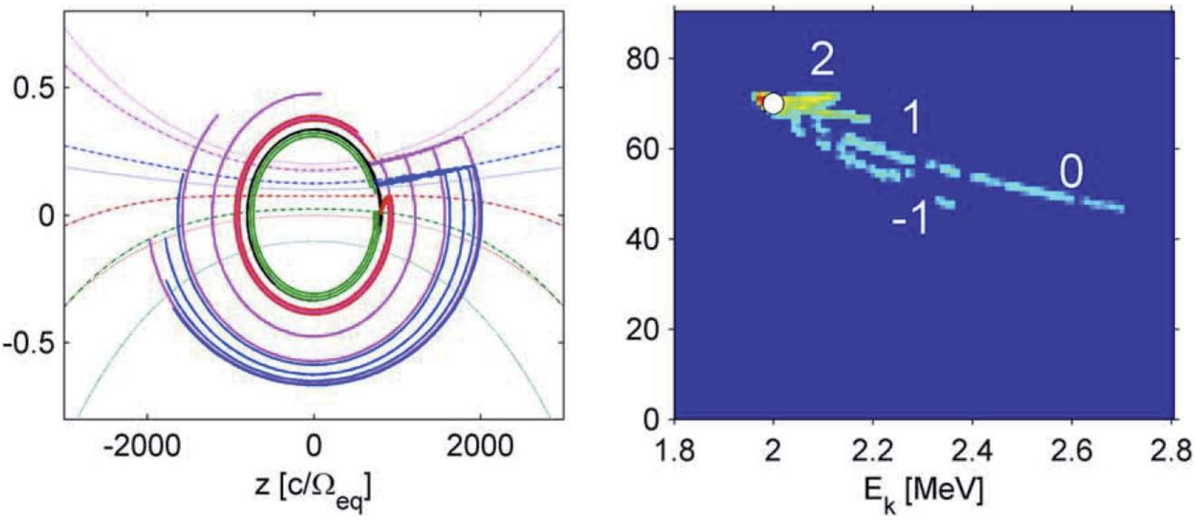

Figure 3. (a) The trajectories of energetic electrons (2 MeV) in the phase space of z and $v_{\|}$. (b) The Green's function in kinetic energy, E_k, and equatorial pitch angle (after Hsieh and Omura [13]).

field rather than the parallel component [13, 15]. Because of the large radius of the cyclotron motion of energetic electrons (> 100 keV) and the perpendicular wavenumber, $k_{\perp}$, there occurs substantial gyro-phase modulation of the wave phase as observed from the electrons, resulting in an effective electric field in resonance with electrons rotating with the cyclotron frequency.

4. Generation of EMIC Rising-Tone Emissions

In the low-frequency range of 0.3 Hz to 3.0 Hz, electromagnetic ion cyclotron (EMIC) rising-tone emissions are often observed in the equatorial region of the inter magnetosphere [16, 17]. Each of the emissions has a subpacket structure such as we found in whistler-chorus emissions [18]. The nonlinear wave growth theory was developed by modifying the theory for chorus emissions [19], and the detailed process of sub-packet formation was reproduced by a hybrid code simulation [7]. Falling-tone emissions were also observed [20], and their mechanism was confirmed by a hybrid simulation [21]. The nonlinear wave growth theory assumes the presence of a proton hole in the velocity phase space, which was confirmed by a hybrid simulation [22]. The nonlinear EMIC wave generation results in precipitation of energetic protons [23, 24].

5. Relativistic Electron Precipitation by EMIC Waves

The EMIC rising-tone emissions can also effectively precipitate relativistic electrons through nonlinear trapping by wave potentials formed at anomalous cyclotron resonance [25, 26]. The frequency variation of the rising tone and the gradient of the magnetic field contribute to changing the pitch angles of relativistic electrons trapped by the wave's potential to lower pitch angles close to the loss cone. As shown in Figure 4, resonant electrons near the loss cone are further scattered into the loss cone by another nonlinear effect, due to the second term in the differential equation of the phase angle ζ, which is an angle between the perpendicular velocity and the wave's magnetic field. The second term is due to the Lorentz force originating from the parallel velocity of the particle as observed in the frame of reference moving with the wave's phase velocity and the wave's magnetic field. The Lorentz force changes the direction of the perpendicular velocities to the direction of the wave's electric field. Since the trapped electrons experience a slow variation of ζ, the perpendicular velocity effectively becomes smaller, being decelerated by the wave's electric field. With the decreasing perpendicular velocity, the particles are rapidly guided into the loss cone rather than following the trajectories of the pendulum equations. This effective scattering is called scattering at low pitch angles (SLPA) [27].

The occurrence of EMIC emissions is limited to a finite range of longitudes. The time scale of EMIC emissions is of the order of one minute, while relativistic electrons can go around the Earth within a few minutes. Since a substantial amount of relativistic electron flux (1 MeV to 3 MeV) can be precipitated by a single EMIC rising-tone emission occurring in a region localized in longitude [28], it is possible to observe echoes of electron depletion in the electron flux of the radiation belt, as observed by spacecraft [27, 29].

6. Suggestions for Future Studies

We now understand that the Earth's outer radiation belt undergoes rapid variations because of nonlinear wave-

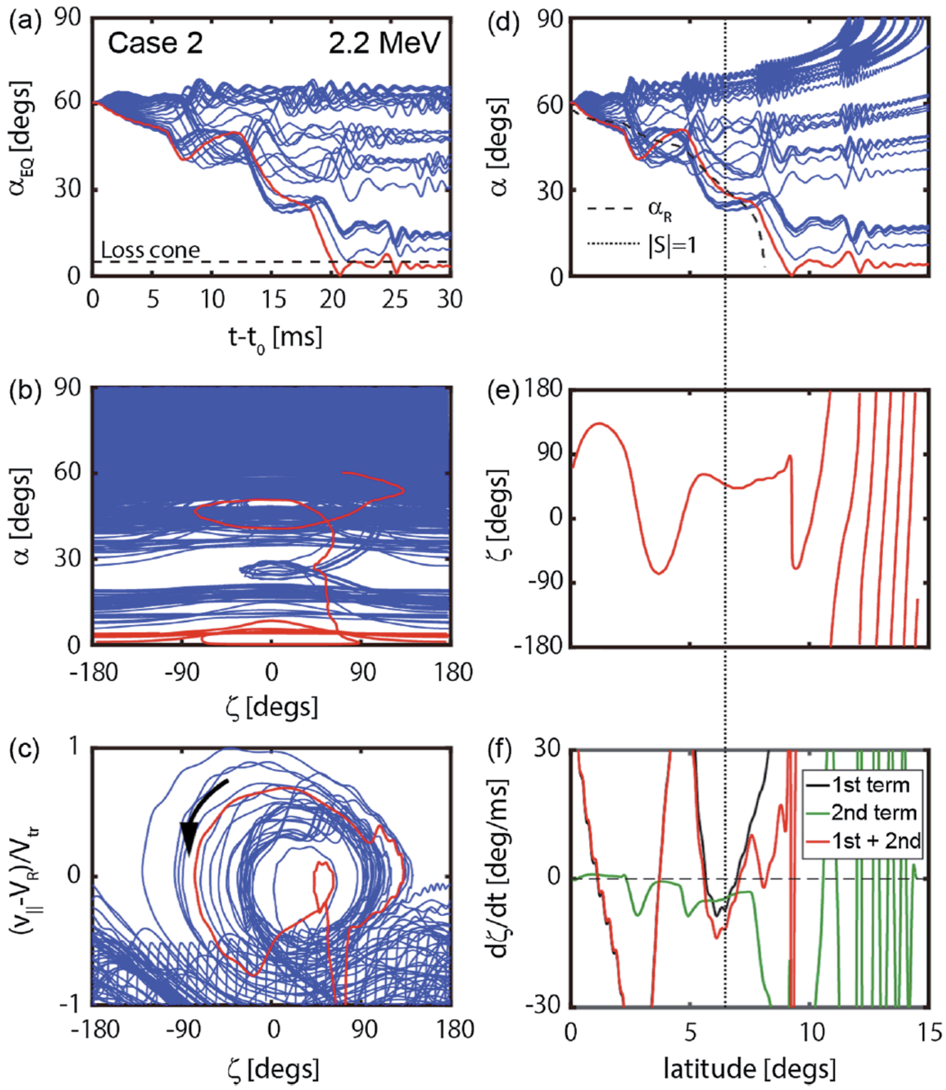

Figure 4. The trajectories of relativistic electrons due to an EMIC rising-tone element with subpackets. The trajectory in red was due to nonlinear trapping and scattering at low pitch angles (SLPA) (after Kubota and Omura [27]).

particle interactions, mostly occurring near the plasmapause. In these nonlinear wave-particle interactions, the rising-tone frequencies of the emissions and the gradient of the magnetic field play essential roles. Since the impacts of both the chorus and EMIC emissions on the acceleration and depletion of the relativistic electrons are significant, the probabilities of the chorus and EMIC emission occurrences need to be evaluated from observations, simulations, and theory. In each series of chorus emissions, the occurrence rates and the intervals of the emissions are necessary for the modeling based on the numerical Green's function method. The relations between these properties of chorus emissions and geomagnetic activities should be statistically clarified. Although the occurrence rate of EMIC emissions is much smaller than that of chorus emissions, we need more statistical studies of EMIC rising-tone emissions. In addition to spacecraft observations, we may also make use of observations of EMIC waves by ground-based magnetometers [30, 31].

We will construct a database of Green's functions of energetic electrons under the influence of chorus and EMIC emissions generated with various physical parameters. Along with the information of the occurrence rates of chorus and EMIC emissions, the repeated numerical convolution integrals of the input electron flux and various sets of Green's functions can reproduce rapid variations of the outer radiation belt. Effects of ULF waves including radial diffusion are yet to be incorporated in future modeling of the whole outer radiation belt.

7. Acknowledgements

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Challenges of Predicting Low-Latitude Ionospheric Scintillations

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Abstract

Two regions of the globe that are most affected by ionospheric scintillations are the auroral region and the low-latitude region encompassing the dip equator. Our present-day dependence on satellite-based communication and navigation has led to a resurgence of interest in the prediction of ionospheric scintillations, which degrade the performance of such systems. In the low-latitude ionosphere, the genesis of intermediate-scale (~100 m to a few km) irregularities, which cause the most severe scintillations on VHF to L-band trans-ionospheric radio signals, is in the growth of the Rayleigh-Taylor (R-T) plasma instability on the bottom-side of the post-sunset equatorial F layer. Theoretical developments and observations by various ground-based instruments, as well as in-situ measurements by instruments onboard rockets and satellites, have identified several parameters of the ambient ionosphere that play key roles in the occurrence of these irregularities over the dip equator. However, the presence of basic conditions for the linear growth of the Rayleigh-Taylor instability fails to explain the large day-to-day variability in the characteristics of these irregularities, which determines the latitudinal distribution and strength of scintillations, and is a result of the nonlinear evolution of the Rayleigh-Taylor instability. In this paper, the present status of the efforts at prediction of low-latitude scintillations on the basis of a multitude of observations and numerical simulation of the development of the Rayleigh-Taylor instability in the equatorial ionosphere are reviewed. In particular, this review describes how observations of ionospheric scintillations may be used to obtain information about the nonlinear evolution of the Rayleigh-Taylor instability under different ambient conditions, which is yet to be explored through numerical simulation of the phenomenon. Such studies have pointed out important gaps in our knowledge about the evolution of equatorial ionospheric irregularities that are responsible for producing scintillations on L-band signals recorded in the equatorial and low-latitude regions around the globe.

1. Introduction

The initiation process for the development of irregularities in the post-sunset equatorial and low-latitude ionospheric plasma that give rise to fluctuations or scintillations in the amplitude and phase of trans-ionospheric VHF and higher frequency radio signals is well known. The presence of irregularities in the equatorial F-region ionosphere that affected the propagation of such radio waves in this region was first seen in ionosonde observations, where the reflected signals showed a "spread" in frequency or range [1]. All the irregularities that occurred in the equatorial F region thus came to be termed equatorial spread F (ESF) irregularities. Dungey [2] was the first to propose that the Rayleigh-Taylor (R-T) instability was responsible for the initiation of equatorial spread F irregularities on the bottom-side of the post-sunset equatorial F region. However, the first observations of the equatorial spread F phenomena from the Jicamarca Radio Observatory (JRO) in Peru brought out the inadequacies of the theories existing at the time for explaining the observations, particularly radar observations indicating the presence of irregularities on the topside of the post-sunset equatorial ionosphere [3]. A breakthrough came with the numerical simulation of the nonlinear development of the collisional Rayleigh-Taylor instability, when a plasma-depleted bubble rises to the linearly stable topside of the equatorial ionosphere [4]. Plumes seen in the range-time-intensity (RTI) maps obtained at Jicamarca Radio Observatory, as well as simultaneous in-situ measurements by a rocket-borne probe, optical observations of a barium cloud released from the rocket, and radar measurements made in Brazil, during equatorial spread F conditions were explained on the basis of upward-moving equatorial plasma bubbles (EPBs) rising from the bottom-side of the post-sunset equatorial F region [5, 6]. Simultaneous measurements of the vertical profile of plasma density using the PLUMEX I rocket probe and the range-time-intensity map of the back-scattered signal of the ALTAIR radar at Kwajalein

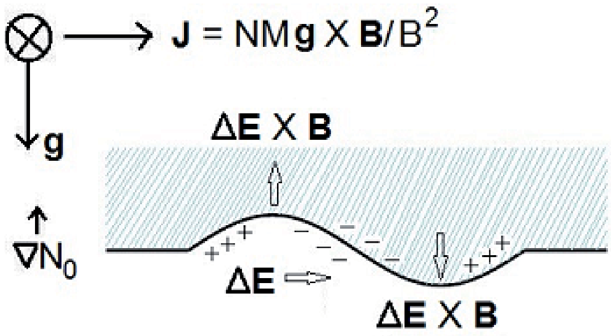

Figure 1. A schematic representation of the initiation of the Rayleigh-Taylor instability on the bottom-side of the post-sunset equatorial F region.

showed that the source region of the strongly back-scattered signal was co-located with a density-depleted region [7]. Similar results emerged from a comparison of ALTAIR range-time-intensity maps with horizontal plasma-density profiles obtained from the Atmospheric Explorer E (AE-E) satellite in-situ data [8]. The picture that emerged was thus that as the equatorial plasma bubbles rise to the top-side of the equatorial F-region in the nonlinear phase of growth of the Rayleigh-Taylor instability, the equatorial ionosphere becomes highly structured, with structures ranging in scale size from hundreds of kilometers down to a few centimeters. As the Rayleigh-Taylor instability involves interchange of entire magnetic flux tubes, an equatorial plasma bubble is elongated along the geomagnetic field. The geomagnetic-field-aligned nature of equatorial plasma bubbles was also established by observations from ALTAIR, a fully steerable radar [9].

The irregularities or structures appearing at different heights in the F region above the dip equator map along the geomagnetic field lines to off-equatorial latitudes. Out of the extended range of spatial scales associated with structures within equatorial plasma bubbles, irregularities with scale sizes in the intermediate range (~100 m to a few km) scatter VHF and higher-frequency radio waves that propagate through the equatorial and low-latitude ionosphere. This scattering produces a spatial pattern of signal amplitude and phase variations in the plane of the receiver. Movement of the irregularities relative to the signal path – either due to drift of the irregularities across the path of a signal transmitted from a geostationary satellite, or due to the signal path sweeping across irregularities as in the case of signals transmitted from orbiting satellites – causes the spatial patterns of signal amplitude and phase variations to move past the receiver. This results in temporal fluctuations in amplitude and phase of the signal recorded by a receiver, which are referred to as scintillations [10, 11]. Strong scintillations, causing deep fades of signal intensity, can result in loss of signal, and rapid phase fluctuations can cause loss of lock for the signal. Intermediate-scale-size irregularities associated with the equatorial plasma bubbles may cover a large part of the low-latitude ionosphere in a particular longitude region on a given night. Therein lies their considerable potential for causing degradation in the performance of satellite-based communication and navigation systems [12]. With the advent of the Global Positioning System (GPS) and later Global Navigation Satellite Systems (GNSS), and large-scale technological dependence on these for navigation, there was a resurgence of interest in the study of ionospheric irregularities and the prediction of scintillations, particularly on L-band signals. Studies of the global distribution of scintillation activity have identified two regions of the globe to be most vulnerable to ionospheric scintillations: the auroral region, and the low-latitude region extending from the dip equator to the equatorial-ionization-anomaly (EIA) regions in both the hemispheres [13, 14]. The physical processes that give rise to scintillation-producing ionospheric irregularities in these two regions are different. As noted earlier, the Rayleigh-Taylor instability initiated on the bottom-side of the post-sunset equatorial F region has been identified as the basic plasma process that ultimately leads to the development of scintillation-producing irregularities in the equatorial and low-latitude ionosphere. The Rayleigh-Taylor instability and scintillations produced by ionospheric irregularities associated with this instability have been studied for several decades. However, the day-to-day variability in the occurrence of these irregularities, their latitudinal extent, and their spatial characteristics, which play critical roles in causing scintillations on signals in different frequency bands, create challenges for prediction of scintillations in the low-latitude regions. Some specific challenges and recent progress made towards identifying the conditions that contribute to the day-to-day variability of not only the occurrence pattern of scintillations but also the latitudinal distribution of scintillations on radio signals of different frequencies are discussed in the next few sections of this article.

2. Seeding of the Rayleigh-Taylor Instability

The process of initiation of the Rayleigh-Taylor instability on the bottom side of the post-sunset equatorial F-region – where the geomagnetic field, $\mathbf{B}$, is horizontal and northward, and a steep upward gradient, ∇N_0, exists in the ambient plasma density, N_0 – is shown in Figure 1. Under the influence of gravity and the geomagnetic field, ions move eastward. Westward movement of the much lighter electrons is negligible, and there is a net eastward current, $\mathbf{J} = N\mathrm{M}\mathbf{g}\times\mathbf{B}/\mathrm{B}^2$, where N is the local plasma density. A perturbation on the bottom-side causes this current to have a divergence, and as a result, charges pile up as shown, producing an eastward-directed perturbation electric field, $\Delta\mathbf{E}$, in the region where plasma density is lower. This electric field gives rise to an upward $\Delta\mathbf{E}\times\mathbf{B}$ drift of the plasma-depleted region, creating an upward-moving equatorial plasma bubble. The linear growth rate of the Rayleigh-Taylor instability showed the importance of the pre-reversal enhancement (PRE) of the eastward

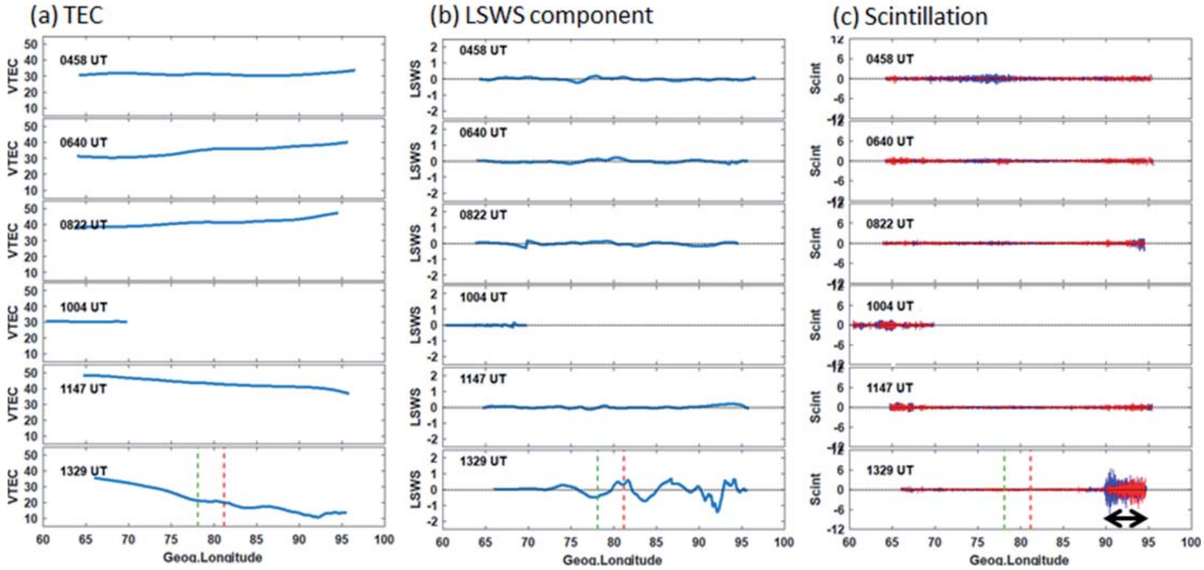

Figure 2. Simultaneous spatial variations of vertical TEC, its large-scale wave-structure component, and amplitude scintillations on 150 MHz and 400 MHz signals observed for six successive orbits of the C/NOFS satellite over Tirunelveli (77.81°E, geomagnetic latitude: 0.08°N). The green and red vertical dotted lines in the bottom panels indicate the locations of the E-region and F-region sunset terminators, respectively. The double-headed arrows in panel (c) indicate amplitude scintillations on both 150 MHz and 400 MHz signals due to the presence of equatorial plasma bubbles on March 31, 2013. The horizontal axis indicates the geographic longitudes of the ionospheric piercing points of the recorded signals (figure courtesy of S. Tulasi Ram).

electric field in the post-sunset equatorial ionosphere, which would raise the equatorial F layer to higher heights, where the ion-neutral collision frequency would be much lower. This would result in a higher growth rate, favoring the occurrence of equatorial spread F. A study of the role of post-sunset equatorial F region vertical plasma drift velocity in the generation and evolution of equatorial spread F using long-term incoherent scatter radar data from the Jicamarca Radio Observatory established that this may be a major cause for the solar-cycle, seasonal, and even day-to-day variability in the occurrence of equatorial spread F [15]. However, longitudinal variability in the occurrence of equatorial spread F, which is characterized by a decorrelation distance as short as a few hundred kilometers, required a more localized explanation. In the early years of study of radar backscatter plumes produced by equatorial spread F irregularities, ALTAIR radar data showed the presence of altitude modulation of electron density contours in the bottom-side of the equatorial F layer prior to plume development [16]. Nearly three decades later, a local upwelling, or quasi-periodic large-scale wave structures (LSWS), on the bottom side of the post-sunset equatorial F layer prior to the occurrence of equatorial spread F started attracting a great deal of attention as a possible source of day-to-day variability in the seeding of the Rayleigh-Taylor instability [17-19]. Figure 2 shows simultaneous observations of spatial variations of vertical total electron content (TEC), its large-scale wave structures component, and amplitude scintillations on 150 MHz and 400 MHz signals observed for six successive orbits of the Communications/Navigation Outage Forecasting System (C/NOFS) satellite over equatorial station Tirunelveli (77.81°E, geomagnetic latitude: 0.08°N). However, the source for upwelling growth, particularly during periods of low solar activity, has not yet been established.

3. Scintillation Prediction Based on Linear Theory of Rayleigh-Taylor Instability

The early linear and nonlinear theories of equatorial spread F [4] considered only the development of an equatorial plasma bubble in the ionosphere over the dip equator. A two-dimensional cross section of an equatorial plasma bubble involving only coordinates transverse to the geomagnetic field was hence considered. As mentioned in the introduction, the Rayleigh-Taylor instability operating in the equatorial ionosphere gives rise to geomagnetic field-aligned equatorial plasma bubbles, which makes it the largest-scale naturally occurring plasma instability in the Earth's ionosphere. In a two-dimensional theory of the Rayleigh-Taylor instability, variations in ionospheric parameters along the geomagnetic field lines in both the hemispheres was taken into consideration by using geomagnetic flux-tube integrated parameters, following the suggestion of G. Haerendel in his famous unpublished preprint ("Theory of Equatorial Spread F," Max Planck Inst. fur Extraterr. Phys., 1973). Several efforts to predict the occurrence of scintillations have been based on a flux-tube integrated linear growth rate of the Rayleigh-Taylor instability derived by Sultan [20]:

$$\gamma_{RT} = \frac{\Sigma_P^F}{\Sigma_P^F + \Sigma_P^E}\left(V_P - U_L^P - \frac{g_e}{\nu_{eff}^F}\right)K^F - R_T . \qquad (1)$$

Here, Σ_P^F and Σ_P^E are flux-tube integrated Pedersen conductivities of the F and E regions of the ionosphere along the geomagnetic field line connecting the equatorial F region with the conjugate E regions in both hemispheres; V_P is the vertical plasma drift at the dip equator due to a zonal electric field; U_L^P is the Pedersen-conductivity-weighted neutral wind perpendicular to the geomagnetic field in the magnetic meridian plane; g_e is the altitude-corrected acceleration due to gravity; ν_{eff}^F is the effective ion-neutral collision frequency weighted by the electron density; K^F is the inverse of the flux-tube electron content vertical gradient scale length; and R_T is the electron density-weighted flux tube recombination rate. In the absence of observational information about the neutral composition, density, and neutral wind, studies of the day-to-day variability in occurrence of equatorial spread F using ionospheric data have focused mostly on the vertical plasma drift at the dip equator, which may be estimated from ionosonde or radar data [15]. In recent years, Carter et al. [21] have used the National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM), driven by the solar F10.7 index and the Kp index, to compute the various terms that contribute to the linear growth rate of the Rayleigh-Taylor instability given in Equation (1), to assess the geomagnetic control of equatorial plasma bubble activity and occurrence of VHF and L-band scintillations at five low-latitude stations located at different longitudes. The Kp index characterizes the level of geomagnetic activity. These authors have further used Kp values based on solar-wind data to drive TIEGCM, in an effort to forecast the occurrence of scintillations on GPS signals recorded at some low-latitude stations in the African and Asian longitude sectors [22]. However, there are some major shortcomings in attempts to predict the strength of scintillations at different latitudes based on the linear growth rate of the Rayleigh-Taylor instability. It is only in the nonlinear phase of development of the Rayleigh-Taylor instability that an equatorial plasma bubble rises to the linearly stable topside of the equatorial ionosphere and develops structure [23]. The height to which the equatorial plasma bubbles rise above the dip equator determines the latitudinal extent of scintillations. It is also well known that while strong VHF scintillations are found to occur at dip equatorial locations as well as at locations in the equatorial-ionization-anomaly region where the ambient F peak plasma density may be significantly higher than the dip equatorial F peak plasma density; L-band scintillations show a distinctly different latitudinal distribution. Generally, L-band scintillations tend to be weak at dip equatorial locations, even when strong L-band scintillations are recorded in the equatorial-ionization-anomaly region [24-26]. This has been attributed to the higher background plasma density, N, in the equatorial-ionization-anomaly region F peak, which would result in a higher density fluctuation, ΔN, in the equatorial-ionization-anomaly region compared to the dip equatorial region, for a given $\Delta N/N$ [26]. However, as discussed in Section 5, enhanced ambient density does not explain the distinctly different relationship between the strengths of VHF and L-band scintillations observed near the dip equator and the equatorial-ionization-anomaly region [27, 28].

4. Scintillation Prediction Based on Three-Dimensional Simulation of Equatorial Plasma Bubble Development?

Equatorial spread F and equatorial plasma bubbles are basically nighttime phenomena. During daytime, currents that flow from the bottom-side of the equatorial F layer, along the geomagnetic field lines for which the electrical conductivity referred to as the direct conductivity is very high, can close through conjugate E layers at the feet of the magnetic field lines, where Pedersen and Hall conductivities are high. This allows currents to flow through

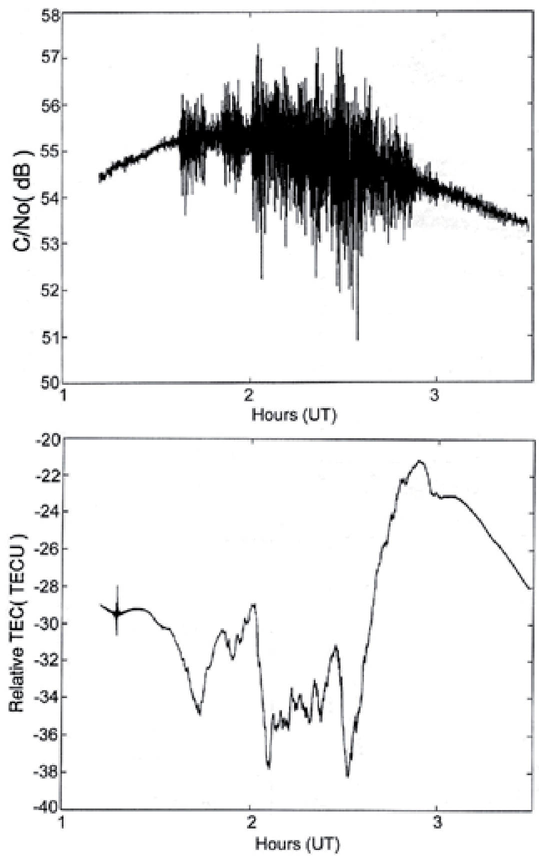

Figure 3. (Top) Fluctuations in the carrier-to-noise ratio on the L1 (1.57542 GHz) GPS signal recorded at an equatorial station, Ancon (77.15°W, geomagnetic latitude 1.07°S), due to amplitude scintillations. (Bottom) The simultaneous variation in relative TEC along the paths of the L1 and L2 (1.2276 GHz) GPS signals recorded at Ancon in the presence of equatorial plasma bubbles (after [34]).

the conjugate E layers in both the hemispheres and back into the bottom-side of the equatorial F-layer, along the nearly perfectly conducting geomagnetic field lines, to short out the perturbation electric field, $\Delta\mathbf{E}$, associated with the Rayleigh-Taylor instability, shown in Figure 1. Once this happens, an equatorial plasma bubble fails to move upwards, and the Rayleigh-Taylor instability does not grow. The time taken to discharge an equatorial plasma bubble is short enough during daytime to prevent the growth of the Rayleigh-Taylor instability [29]. This aspect of equatorial plasma bubble development, as well as mapping of irregularities formed at different altitudes over the dip equator to off-equatorial F regions along geomagnetic field lines, require three-dimensional simulation of the nonlinear development of equatorial plasma bubbles [23, 30-32]. For the computation of scintillation using a phase-screen approximation [10], fluctuations in total electron content (TEC) along the path of an incident radio signal caused by the presence of equatorial plasma bubbles and associated irregularities are used to estimate the phase variations that would be imposed on the incident radio signal by all the irregularities in its path. This information is then used to generate an equivalent phase-changing screen in the path of the signal located near the peak of the F region, and amplitude scintillations are computed [33]. An example of variation in TEC along the paths of the L1 (1.57542 GHz) and L2 (1.2276 GHz) GPS signals recorded at an equatorial station, Ancon, in the presence of equatorial plasma bubbles is shown in the bottom panel of Figure 3. The relative TEC, uncertain to an additive constant, was derived from the respective number of cycles, including fractional cycles, of L1 and L2 carriers recorded by a dual-frequency receiver after it locked onto the signal. Simultaneous variations in the carrier-to-noise ratio on L1 due to amplitude scintillations are shown in the top panel of Figure 3 [34]. Earlier three-dimensional simulations of equatorial plasma-bubble development [30-33] did not have adequate spatial resolution to delineate the intermediate-scale irregularities that cause scintillations on VHF and higher-frequency signals. However, simulation results obtained by Retterer [33], with a spatial resolution of 10 km, showed that in pre-midnight hours, the power spectrum of spatial variations in the magnetic east-west direction of the vertical TEC, down to a scale size of 20 km, was significantly shallower in the equatorial-ionization-anomaly region as compared to the equatorial region. More recently, a high-resolution bubble (HIRB) model was developed by Yokoyama [23], where a zonal resolution of 333.6 m was achieved. With further improvement in spatial resolution and the use of a model with realistically evolving background ionosphere, future high-resolution bubble model simulations would pave the way towards significant progress in prediction of low-latitude ionospheric scintillations. In the absence of realistic three-dimensional simulations of equatorial plasma bubble development with adequate spatial resolution for prediction of scintillations, observations of multi-frequency scintillations at different latitudes may be used to derive important information about the evolution of the irregularities associated with equatorial plasma bubbles that cause scintillations. This aspect is described in the next section, as such information provides a basis for new efforts to predict scintillations at dip equatorial and low latitudes.

5. Latitudinal Distribution of VHF and L-Band Scintillations

As mentioned in Section 3, during pre-midnight hours strong VHF scintillations are often accompanied by moderate-to-strong L-band scintillations in the equatorial-ionization-anomaly region, with the crest of the equatorial-ionization-anomaly region generally located around 15° geomagnetic latitude in the two hemispheres. However, in the dip equatorial region, strong VHF scintillations are accompanied by weak L-band scintillations [24-26]. An example of this is shown in Figure 4. The S_4 index plotted in this figure is the standard deviation of fluctuations in normalized signal intensity, and is used to indicate the strength of amplitude scintillations. In Figures 4a and 4b, respective S_4 indices were computed from amplitude scintillations on a 251 MHz signal transmitted from a geostationary satellite located at 72.4°E and recorded at two locations in the dip equatorial and equatorial-ionization-anomaly regions in the Indian longitude zone. The coordinates of the ionospheric penetration point (IPP) of the signal path at an altitude of 300 km for both of the cases are given in the figures. The geomagnetic latitudes of the ionospheric penetration points were 0.23°S at the dip equatorial location and 9.87°N at the off-equatorial location in the equatorial-ionization-anomaly region. The signal-path elevation angles for the two locations were 78° and 67.6°, respectively. The S_4 indices computed from amplitude scintillations on a 1.575 GHz signal transmitted from the geostationary satellite GSAT-10, located at 83°E, and recorded in dip equatorial and equatorial-ionization-anomaly regions, are shown respectively in Figures 4c and 4d. In this case, the geomagnetic latitudes of the ionospheric penetration points were 0.43°S at the dip equatorial location and 9.81°N at the off-equatorial location in the equatorial-ionization-anomaly region. The signal-path elevation angles for the two locations were 77.8° and 65°, respectively. It is thus seen that for both the VHF and L-band signals recorded at each location, not only are the ionospheric penetration points close enough to assume that the signals were propagating through the same volume of irregularities near the F-region peak, but the elevation angles were also nearly equal. This ensured that the signal-path lengths within the effective irregularity layer near the F-region peak were nearly identical for both the VHF and L-band signals. In the dip equatorial region, strong VHF scintillations were recorded on this day, with the VHF index often exceeding 1. At the same time, L-band scintillations recorded at the equatorial location were weak, with $S_4 < 0.2$. The picture was entirely different in the equatorial-ionization-anomaly region as seen in Figures 4b and 4d. Strong VHF scintillations were recorded here as well, but S_4 did not exceed 1. On the other hand, L-band

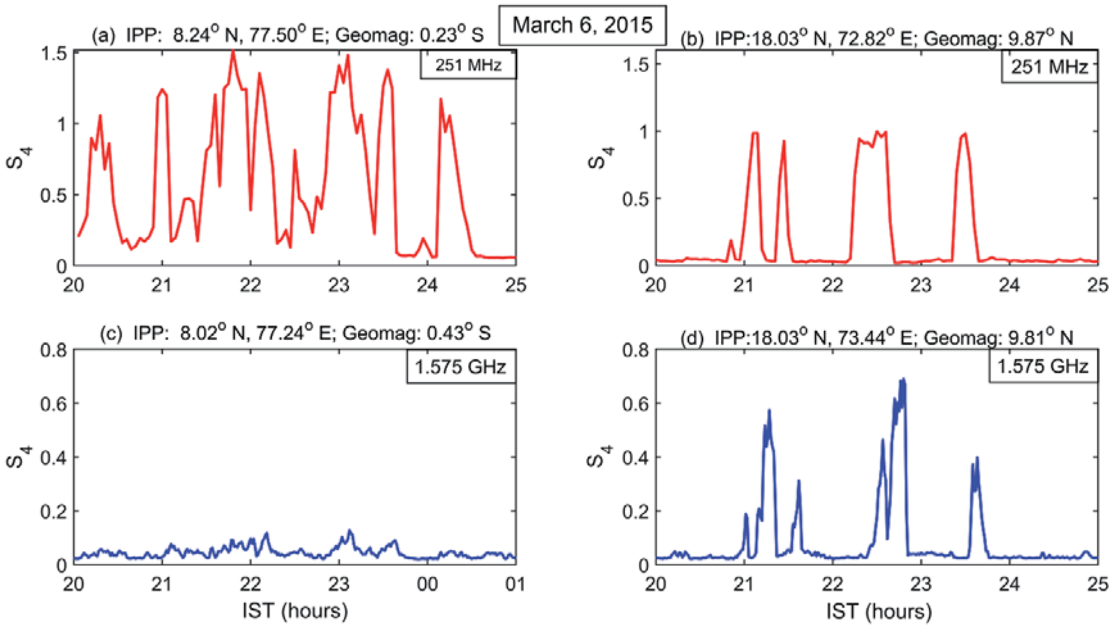

Figure 4. **S_4 indices estimated from amplitude scintillations on 251 MHz and 1.575 GHz signals transmitted from geostationary satellites and recorded in dip equatorial and equatorial-ionization-anomaly regions in the Indian longitude zone, as functions of Indian standard time (IST), on March 6, 2015. The coordinates of the respective ionospheric penetration points (IPPs) are given in the figures.**

scintillations here were much stronger than near the dip equator. In order to understand how this happened, it was necessary to carry out model calculations of S_4 [27], as described in the next section.

5.1 Model Calculation of S_4 Index

A two-dimensional model of the irregularities is often used to calculate S_4 indices for different irregularity characteristics, since equatorial plasma bubbles and associated irregularities are aligned with the geomagnetic field, assumed to be along the y axis. Since the irregularity-scale sizes involved are much longer than the signal wavelength, radio waves are also essentially scattered in the forward direction close to their propagation paths. The x axis is taken to be in the magnetic east-west direction, so that electron-density variations and associated refractive-index variations depend only on the x and z coordinates. The incident radio wave is assumed to propagate along the z direction. The S_4 index is a special case of the fourth moment, Γ_4, of the complex amplitude, $u(x,z)$, of the radio wave [10]:

$$\Gamma_4(x_1,x_2,x_3,x_4,z)$$
$$=\left\langle u(x_1,z)u(x_2,z)u^*(x_3,z)u^*(x_4,z)\right\rangle, \qquad (2)$$

where the angular brackets denote an ensemble average. As the signal propagates through the irregularity layer followed by empty space to the ground receiver, Γ_4 satisfies an equation at each point along the path. This equation describes the change in Γ_4 along the propagation path due to contributions from the phase perturbation imposed by the irregularities as well as forward propagation [10]. In situ measurements of plasma-density fluctuations associated with equatorial plasma bubbles in the low-latitude ionosphere using instruments onboard satellites have shown that irregularities in the intermediate-scale range may be described by a power-law type of one-dimensional spectrum [35, 36]. In the two-dimensional models, an isotropic single-component power-law irregularity spectrum with slope $-m$ is often used to characterize the intermediate-scale equatorial spread-F irregularities. A simple power-law spectrum of the form $\Phi_{\Delta N}(q) \propto q^{-m}$ holds for intermediate scales that are much longer than the inner scale, r_0, and much shorter than the outer scale, R_0, which characterize the irregularity spectra obtained from in situ measurements. The fourth-moment equation may be solved using a split-step method, in which the irregularity layer is considered to consist of multiple phase screens, interspersed with free space between the phase screens [37].

In equatorial plasma bubble simulations, density fluctuations associated with equatorial plasma bubble irregularities are sometimes mentioned as a percentage of the background plasma density, N. However, the strength of scintillations is determined by $\sigma_{\Delta N}$, the standard deviation of electron-density fluctuations, and not by $\sigma_{\Delta N}/N$. In Figure 5, S_4 values for 251 MHz and 1.575 GHz signals – obtained by solving the 4th moment equation [27] – are plotted as functions of $\sigma_{\Delta N}/N$ for a particular background plasma density, N, specified in terms of the

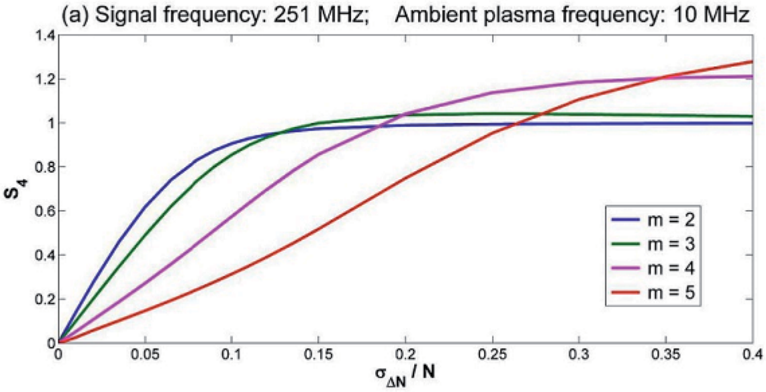

Figure 5a. S_4 **indices computed for an incident radio signal of frequency 251 MHz as a function of the standard deviation of normalized electron density fluctuations, with** N **being the ambient plasma density. The irregularities were characterized by a power-law irregularity spectrum with slope** $-m$**. Four values of** m **were considered, keeping other irregularity parameters the same (after [27]).**

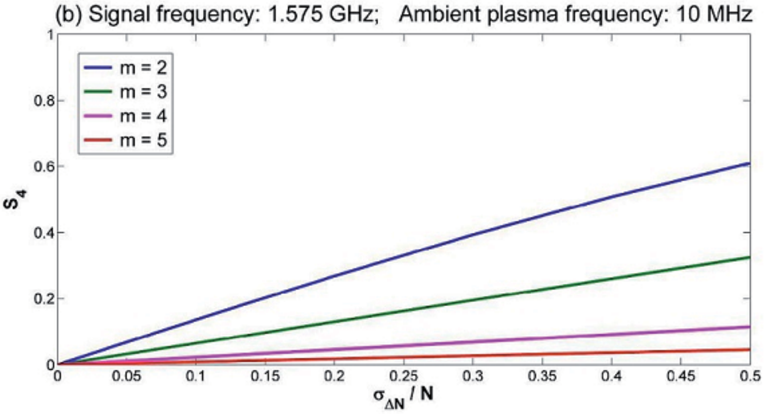

Figure 5b. The same as for Figure 5a for a signal of frequency 1.575 GHz (after [27]).

ambient plasma frequency, $f_P = \left(Ne^2 / \pi m_e \right)^{1/2}$,where e and m_e are the charge and mass of an electron. An increase in N would imply an increased irregularity strength, $\sigma_{\Delta N}$, for a given $\sigma_{\Delta N}/N$. In this figure, the irregularity power-law spectral index was varied from $m = 2$, which corresponded to a shallow irregularity spectrum, to $m = 5$ corresponding to a steep irregularity spectrum. Other irregularity parameters used to compute S_4 were $r_0 = 10$ m; $R_0 = 10$ km; the thickness of the irregularity layer, $L = 50$ km; and the distance of the ground receiver from the top of the irregularity layer, along the signal path, was 350 km. An important result that emerged from these calculations was that when the irregularities were characterized by a steep power-law spectrum, the L-band S_4 index remained small, even if the irregularity strength was increased by a factor of 10 [27]! However, the VHF S_4 may, in this case, exceed 1 with increasing $\sigma_{\Delta N}$. The VHF result was in agreement with the asymptotic expressions for S_4 derived by Rino [38] for very strong scattering by a one-dimensional phase screen. Those showed that whereas the S_4 index asymptotically approached unity from below for $1 < m < 3$, S_4 may exceed 1 for $m \geq 3$. For steeper spectra, S_4 values greater than 1 were attributed to strong focusing of the signal by larger-scale irregularities, since small-scale structures that are more effective in scattering the radio waves, and therefore destroy the focusing effects of the large-scale irregularities, were absent. These model calculations provided an explanation for the VHF and L-band scintillations observed in the equatorial and equatorial-ionization-anomaly regions [27], an example of which is seen in Figure 4. At a particular latitude, the maximum contribution to scintillations came from irregularities in the F peak region, where the background plasma density was maximum. This first study of VHF and L-band scintillations in the dip equatorial and equatorial-ionization-anomaly regions showed that the intermediate-scale irregularity spectrum may be much steeper around the equatorial F peak region as compared to the F peak in the equatorial-ionization-anomaly region [27]. High-resolution bubble-model simulations of equatorial plasma bubble development [23] have clearly demonstrated that the topside of the equatorial F region is more structured than the region near the equatorial F peak. In a recent paper [39], high-resolution bubble-model simulation results were used to obtain stochastic structure in evolving equatorial plasma bubbles in three slice planes perpendicular to the geomagnetic field: one at the dip equator and two others at different off-equatorial geomagnetic latitudes. The results showed that structures from the topside of the equatorial F region, above 500 km, were mapped along geomagnetic field lines to the F-region peak (around 350 km) in the offset 2 slice plane. The results obtained from VHF and L-band scintillation observations and modeling may thus be interpreted to indicate that irregularities from the topside of the equatorial F region, which have a shallower spectrum compared to the irregularities near the equatorial F-region peak, map down to F peak in the equatorial-ionization-anomaly region, and cause moderate to strong L-band scintillations when L-band scintillations in the dip equatorial region are weak.

5.2 Signal-Frequency Dependence of Ionospheric Scintillations

As discussed in Section 5.1, a new result that emerged from a study of VHF and L-band scintillations in the dip equatorial and equatorial-ionization-anomaly regions is that the signal frequency dependence of ionospheric scintillations is a pointer to the nature of the power-law spectrum of the equatorial spread-F irregularities that are present in the neighborhood of the F-region peaks at different latitudes, in the post-sunset equatorial and low-latitude ionosphere [27]. Theoretically, the phase-screen approximation has been used to derive the signal-frequency dependence of weak scintillations produced by geomagnetic field-aligned two-dimensional isotropic irregularities characterized by a single-component power-law spectrum with slope $-m$, and with an outer scale much greater than the Fresnel scale ($=\sqrt{2\lambda z_R}$), where z_R is the distance of the phase screen from the receiver. In this case, a simple relationship was found between S_4 and the signal frequency, f : $S_4 \propto f^{-n}$, where $n=(m+3)/4$ [28]. For scintillations that cannot be classified as weak, S_4 indices for 251 MHz and 1.575 GHz signals were computed for varying irregularity strengths by solving the fourth-moment equation as described in Section 5.1. Slopes of the irregularity spectra, assumed to be of power-law form, were varied from -2 to -5. In situ measurements [36] as well as high-resolution bubble-model simulation results indicated that the developed structures within equatorial plasma bubbles were sometimes characterized by a two-component power-law spectrum. No analytical results exist for two-component irregularity spectra. Model computations of S_4 were therefore also carried out for two-component power-law irregularity spectra with a shallow spectral index, $m_1=2$, and a steep spectral index, $m_2=4$, and break scales varying between 250 m and 4 km. The theoretical results were compared with the frequency exponent, n, derived from amplitude scintillations recorded on a 251 MHz signal and a 1.575 GHz signal transmitted from geostationary satellites and recorded in the dip equatorial and equatorial-ionization-anomaly regions, an example of which is shown in Figure 4. S_4 indices on these two frequencies, f_1 and f_2, were used to obtain n:

$$n(f_1/f_2)=-\frac{\log\left[S_4(f_1)/S_4(f_2)\right]}{\log(f_1/f_2)}. \tag{3}$$

Comparison of n, as a function of L-band S_4 derived from VHF and L-band scintillations recorded at the two locations on several days, with the theoretical results obtained from model calculations for power-law irregularity spectra with different specifications, clearly showed, for the first time, the distinct nature of the power-law spectra at the two locations. The slope of the irregularity power-law spectrum near the peak of the post-sunset equatorial ionospheric F region was seen to be steep ($m \geq 4$), whereas the irregularity power-law spectrum in the equatorial-ionization-anomaly F peak region was much shallower $(m \leq 2)$ before the irregularities started to decay [28]. These results established the critical role of the irregularity spectrum in giving rise to the much stronger L-band scintillations in the equatorial-ionization-anomaly region in comparison to the dip equatorial region. A much higher ambient plasma density would fail to give rise to strong L-band scintillations observed in the equatorial-ionization-anomaly region, if the irregularity power-law spectrum had a slope as steep as that found in the equatorial case. It is thus now clear that for prediction of ionospheric scintillations in the low latitudes, it is necessary to include information of how intermediate-scale irregularities develop at different altitudes within an equatorial plasma bubble under different ambient conditions.

6. Spatial Coherence Scale of Ground Scintillation Pattern

In earlier work using spaced-receiver amplitude scintillation data on a VHF signal transmitted from a geostationary satellite and recorded at a dip equatorial location, the spatial coherence scale of the ground scintillation pattern was studied to understand the evolution of intermediate scale structure within equatorial plasma bubbles in different seasons [40]. Spaced-receiver amplitude scintillation data provides additional information regarding the dynamics of ionospheric irregularities besides the S_4 index and spectrum of scintillations. As seen from Figure 6, other parameters that may be derived from such data include the average drift speed, V_0, of the ground scintillation pattern along the receivers' baseline, and a parameter V_C referred to as a "random" or "characteristic velocity" in the literature [11]. For Figure 6, amplitude scintillation data for a 251 MHz signal recorded by two receivers spaced along a magnetic east-west baseline at an equatorial station were used. As mentioned earlier, movement of the ground scintillation pattern along the receivers' baseline depends on the speed with which irregularities drift across the signal path. The parameter V_C may be related to the standard deviation of fluctuations in irregularity drift [41]. In Figure 6, S_4, V_0, and V_C, computed for each three-minute interval during the scintillation event, were plotted. The parameter $C_I(x_0, t_m)$, where x_0 is the distance between the two receivers, is the maximum cross correlation, found at time lag t_m, for each three-minute interval. This parameter may be used to delineate nascent equatorial plasma bubbles from fossilized equatorial plasma bubbles, for which the perturbation electric field, $\Delta\mathbf{E}$, associated with the Rayleigh-Taylor instability, has decayed, so that the equatorial plasma bubble is not evolving any more. The fossilized equatorial plasma bubbles simply drift with the background plasma as fluctuations in irregularity drift arising from $\Delta\mathbf{E}$ are nearly zero, and the signals recorded by the spaced receivers are well correlated, resulting in $C_I(x_0, t_m)$ values close to unity, as seen in Figure 6

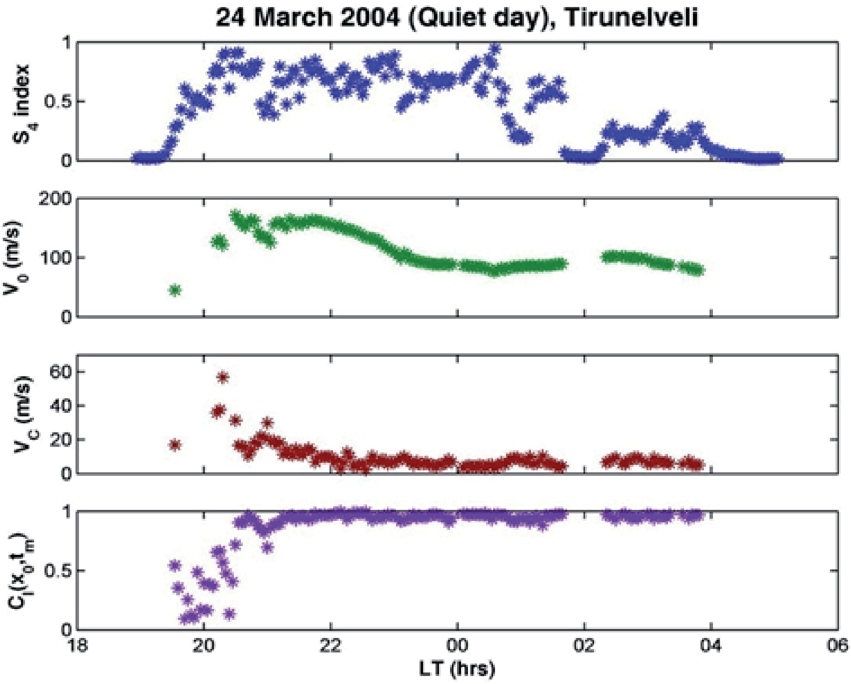

Figure 6. The temporal variation of parameters estimated from amplitude scintillations on a 251 MHz signal transmitted from a geostationary satellite and recorded by two spaced receivers placed 540 m apart along a magnetic east-west baseline at an equatorial station, Tirunelveli. From the top, the parameters were the S_4 index; the average drift speed, V_0, of the ground scintillation pattern along the receivers' baseline; a parameter, V_C, related to the standard deviation of fluctuations in irregularity drift; and the maximum cross correlation between the two signals, $C_I(x_0, t_m)$, where x_0 is the distance between the two receivers and t_m is the time lag for maximum cross correlation. All the parameters were estimated for each three-minute interval during the scintillation event recorded on this day, which was a magnetically quiet day.

[41]. This feature of $C_I(x_0, t_m)$ provides a technique for identifying scintillations produced by equatorial plasma bubbles generated at the longitude of the receiver due to a magnetic storm, as opposed to scintillations caused by irregularities that developed at an earlier time, to the west of the receiver location, and that later drifted eastward with the ambient plasma into the path of the received signal [42]. For the calculation of V_0 and V_C, the space-time correlation function of intensity variations in the ground scintillation pattern was assumed to be of a form that takes into account the possibility of decorrelation of spaced receiver signals [43]:

$$C_I(x,t) = F\left[(x - V_0 t)^2 + V_C^2 t^2\right]. \tag{4}$$

The functional form of F is not required for the computation of V_0 and V_C, but it is assumed that F is a monotonically decreasing function of its argument, with $F(0) = 1$. With the x axis along the baseline of the receivers, which is in the magnetic east-west direction, it is seen from Equation (4) that

$$C_I(x_0, t_m) = F\left[x_0^2 V_C^2 \big/ \left(V_C^2 + V_0^2\right)\right]. \tag{5}$$

In Equation (5), since $C_I(x_0, t_m)$, x_0, V_0, and V_C are estimated from spaced-receiver scintillation data, it is possible to characterize the functional form of F by plotting $C_I(x_0, t_m)$ versus $x_0 V_C \big/ \left(V_0^2 + V_C^2\right)^{1/2}$, as was done in Figure 7. This is equivalent to a plot of the spatial correlation function, $C_I(x, 0)$, as a function of x. It was seen that the spatial correlation functions estimated in this manner were reasonably well approximated by a Gaussian. The ground scintillation pattern for each three-min interval could thus be characterized by a coherence scale length [25]:

$$C_I(x, 0) = F\left[x^2\right] = \exp\left[-0.693 (x/d_I)^2\right]. \tag{6}$$

Theoretically, the dependence of d_I on the irregularity spectrum may be evaluated by solving the fourth-moment Equation (3) to obtain the spatial correlation function $C_I(x, 0)$ by considering a two-dimensional model of the irregularities, as described in Section 5.1 [40, 44]. For weak scintillations, d_I is basically determined by the Fresnel scale, so that $d_I \propto \sqrt{z_R}$, where z_R is the average distance of the irregularity layer from the receiver along the signal path. There is also a dependence on the spectral index, m, of a power-law spectrum for the irregularities. However, it is not possible to delineate this dependence on

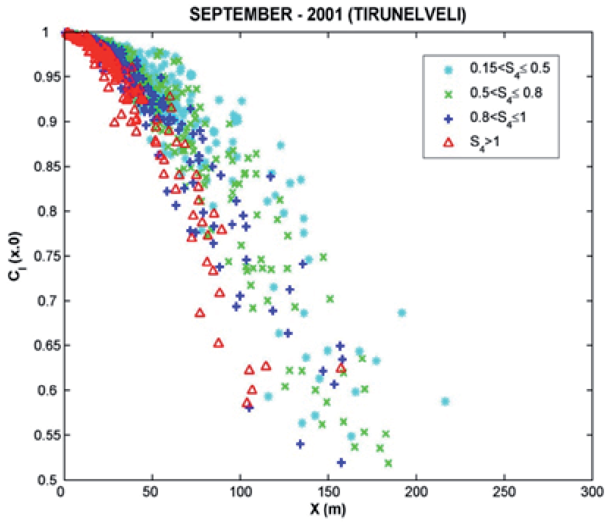

Figure 7. A scatter plot of $C_I\left(x_0, t_m\right)$ as a function of $x_0 V_C \big/ \left(V_0^2 + V_C^2\right)^{1/2}$, which is equivalent to a scatter plot of the spatial correlation function, $C_I(x,0)$, of the ground scintillation pattern as a function of the spatial lag, x, for each three-minute interval of all the scintillation events recorded by spaced receivers at equatorial station Tirunelveli, on a 251 MHz signal transmitted from a geostationary satellite during the month of September 2001. The points in the plot were color-coded according to the corresponding values of S_4. The four groups of S_4 values extended from weak scintillations ($S_4 \le 0.5$) to saturated scintillations ($S_4 > 1$). This showed how the coherence scale, which characterizes the ground scintillation pattern, changed with the strength of scintillations.

the spectral slope because as an equatorial plasma bubble evolves, its altitude keeps changing, so that d_I extracted from weak and moderate scintillations would also vary on account of changes in z_R. On the other hand, model calculations show that for saturated scintillations with $S_4 \ge 1$, d_I becomes independent of z_R, but d_I increases with increasing m: an absence of shorter-scale-length irregularities increases d_I. The dependence of d_I on the spectral slope for saturated scintillations may thus be used to study the evolution of the irregularity spectrum during different stages of equatorial plasma bubble development and decay using spaced-receiver scintillation data [40]. As mentioned earlier, another parameter that is closely linked with equatorial plasma bubble evolution is V_C. In the initial stage of development of an equatorial plasma bubble, V_C rapidly increases. This is the phase when the equatorial plasma bubble rises to the topside of the equatorial F layer, due to the perturbation electric field, $\Delta\mathbf{E}$, associated with the Rayleigh-Taylor instability. Theoretical modeling of the space-time variation of the ground intensity pattern under different scintillation regimes was carried out in the past [11]. It was concluded from these studies that for irregularities that drift across the signal path with an average speed V_0, accompanied by random fluctuations in the drift speed with a standard deviation σ_V, the random velocity, V_C, may be interpreted as a measure of σ_V. The relationship of σ_V with the standard deviation of plasma-density fluctuations produced by the nonlinear growth of the Rayleigh-Taylor instability is as follows [45]:

$$\sigma_V^2 = 0.5\left(\frac{g}{\nu_{in}}\right)^2 \left\langle \frac{|\Delta N|^2}{N_0^2} \right\rangle, \qquad (7)$$

where g is the acceleration due to gravity and ν_{in} is the ion-neutral collision frequency. After an equatorial plasma bubble stops rising, it comes down to lower altitudes with the downward-drifting ambient plasma to a region of higher ν_{in}, resulting in lower σ_V and V_C even while $\sigma_{\Delta N}$ remains the same. The plasma-density structures that give rise to scintillations therefore remain while V_C decreases [41]. The

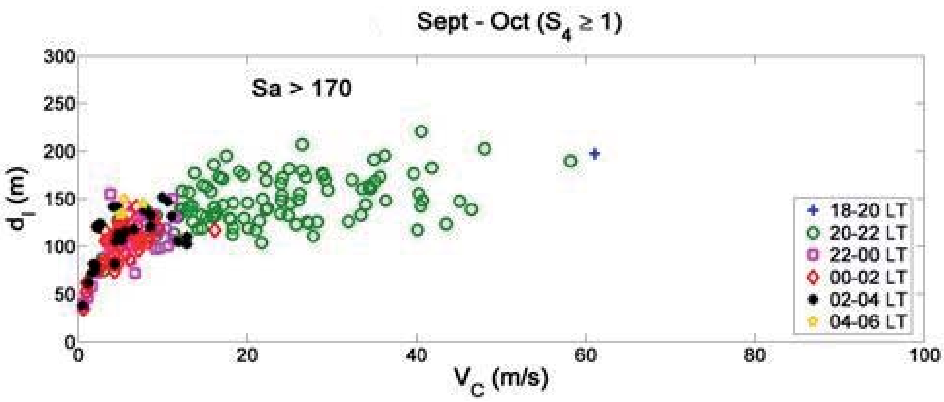

Figure 8. A scatter plot of the coherence scale, d_I, of the ground scintillation pattern as a function of V_C for saturated scintillations ($S_4 \ge 1$) recorded at an equatorial station, Tirunelveli, during scintillation events that occurred in the equinoctial months of September and October on days with high UV solar flux, indicated by the adjusted $F_{10.7}$ index (Sa) > 170 during the years 1995-2006. The points were color-coded according to local time (LT). This showed how the ground scintillation pattern changed as the irregularities evolved with time.

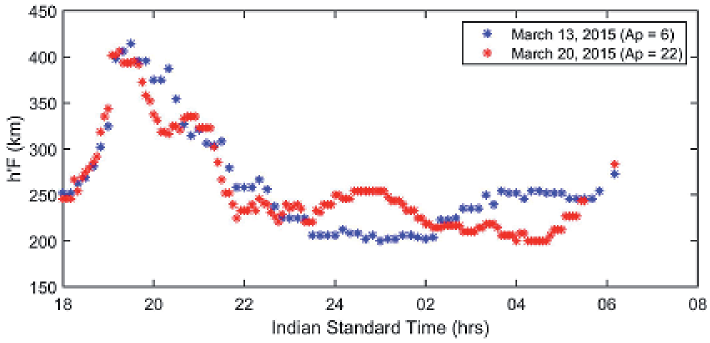

Figure 9. The variation of h′F obtained at the dip equatorial station Tirunelveli during the post-sunset hours of March 13 and 20, 2015 (after [28]).

irregularities finally decay due to diffusion, resulting in the gradual disappearance of scintillations as indicated by the S_4 index. A plot of d_I as a function of V_C for only saturated VHF scintillations ($S_4 \geq 1$) recorded at an equatorial station during a number of scintillation events that occurred in the equinoctial months of September and October on days with high UV solar flux, indicated by adjusted $F_{10.7}$ (Sa) > 170, is displayed in Figure 8. This plot shows that in the initial stages of equatorial plasma bubble development during 20-22 LT (local time), when an equatorial plasma bubble rose rapidly and developed intermediate-scale structure, V_C increased rapidly while d_I, which was independent of height for saturated scintillations, remained nearly constant and had the largest values during a scintillation event recorded in the equatorial region. Comparison with model results for d_I indicated that in the post-sunset equatorial ionosphere, when an equatorial plasma bubble was highly structured on the topside of the equatorial F layer, the irregularity spectrum in the equatorial F peak region was characterized by a steep slope ($m \geq 4$) [40].

7. Latitudinal Extent of Scintillations Due to Equatorial Plasma Bubbles

There are two aspects of the nonlinear development of equatorial plasma bubbles that determine the latitudinal distribution of ionospheric scintillations caused by intermediate-scale irregularities associated with the equatorial plasma bubbles. As discussed in the previous sections, development of structure within the equatorial plasma bubbles as they rise to the topside of the equatorial F layer, and the resulting altitude-dependent irregularity spectra along the magnetic east-west direction over the dip equator, are one set of aspects. This explains the occurrence of weak L-band scintillations near the dip equator when strong L-band scintillations are recorded in the equatorial-ionization-anomaly region. The other aspect of nonlinear development of equatorial plasma bubbles that determines the latitudinal extent of the observed scintillations is the maximum height to which the equatorial plasma bubbles rise. According to a linear theory, in the initial stage of growth of a plasma bubble the magnitude of its velocity of rise over the dip equator is given by [46]

$$V = \frac{\Delta N}{N_0}\left(\frac{g}{\nu_{in}} + \frac{cE_0}{B}\right), \qquad (8)$$

where an ambient equatorial zonal electric field, E_0 which is also generally present has been included, and B is the geomagnetic field at the dip equator. This equation shows that not only the ambient ionospheric conditions but also the thermospheric conditions can significantly alter the initial velocity of rise of an equatorial plasma bubble, because the neutral component comes into the picture through the ion-neutral collision frequency, ν_{in}. However, only a simulation of the nonlinear evolution of equatorial plasma bubbles can provide an answer to the question, When does an equatorial plasma bubble stop rising? Such a simulation demonstrated that an equatorial plasma bubble stops rising when the magnetic-flux-tube-integrated ion-mass density inside the bubble equals that of the surrounding background ionosphere [47]. On magnetically quiet days, post-sunset, the equatorial zonal electric field becomes westward, and the background ionosphere descends even as an equatorial plasma bubble rises through it. There may be two days with a similar rate of descent of the background equatorial ionosphere from the same maximum height, and both days have equatorial plasma bubbles that start developing at the same height. On the day when equatorial plasma bubbles rise at a slower speed, the magnetic-flux-tube-integrated ion-mass density inside a bubble would equal that of the surrounding background ionosphere when the equatorial plasma bubbles are at a lower height. The equatorial plasma bubbles thus would stop rising at a lower height compared to the other day. This impacts the latitudinal extent of scintillations caused by equatorial plasma bubble irregularities. An example of this is presented in Figures 9 and 10. Figure 9 shows the variations of the virtual height, h′F, of the equatorial F layer during the post-sunset hours on a magnetically quiet day, March 13, 2015, and on March 20, 2015, which was preceded by periods of significant magnetic activity. On both days, there was significant pre-reversal enhancement of the eastward electric field in the post-sunset equatorial ionosphere, raising the equatorial F layer to approximately the same maximum height, followed by a descent of the ionosphere at almost the same rate when the ambient electric field turned westward. However, as is evident from Figure 10 where the latitudinal distribution of L-band scintillations is

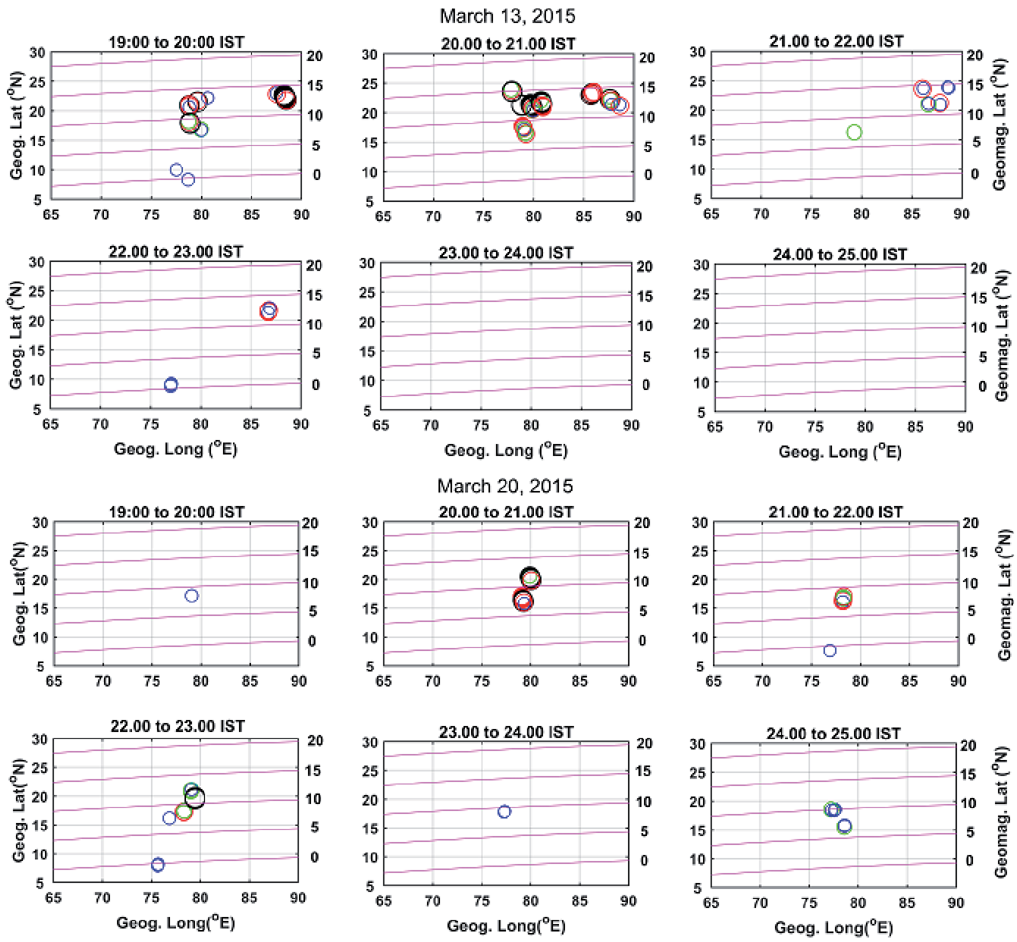

Figure 10. The spatial and temporal variations of L-band scintillations recorded by a network of receivers in the Indian longitude zone for all visible non-geostationary GNSS satellites during periods when the signal-path elevation angle was not less than 55°. The circles of different colors and sizes indicate the levels of five-minute averages of L-band S_4 indices computed along the tracks of the ionospheric penetration points at 300 km altitude for each satellite: (top) on March 13, 2015, and (bottom) on March 20, 2015. Four different levels of S_4 are shown: (1) blue circles for $0.15 \leq S_4 \leq 0.25$; (2) green circles for $0.25 \leq S_4 \leq 0.35$; (3) red circles for $0.35 \leq S_4 \leq 0.5$; and (4) black circles for $S_4 > 0.5$. The geomagnetic latitudes are displayed as mauve lines with the corresponding geomagnetic latitudes at 90°E longitude marked on the right-hand side axes (after [28]).

displayed, the equatorial plasma bubbles stopped rising at a lower height on March 20 as compared to March 13. In the absence of thermospheric data, the Coupled Thermosphere, Ionosphere, Plasmasphere, and Electrodynamics (CTIPe) model was used to determine thermospheric conditions on these two days. The results showed that concentration of atomic oxygen was significantly larger on March 20 compared to March 13, 2015 [48]. Magnetic activity, which is known to alter the post-sunset equatorial zonal electric field on some occasions, and hence to impact the development of equatorial plasma bubbles and associated irregularities that cause scintillations [42], may thus also have a delayed effect on thermospheric density. This alters ν_{in}, and hence impacts the maximum altitude to which equatorial plasma bubbles rise, which in turn determines the latitudinal extent of ionospheric scintillations.

8. Conclusions

There have been numerous attempts to predict post-sunset low-latitude ionospheric scintillations [21, 22, 24, 33], as these can give rise to the most deleterious effects on the performance of satellite-based communication and navigation systems such as GNSS, particularly near the crest of the equatorial-ionization-anomaly region, during solar-cycle maximum periods [13, 14]. Nearly all such efforts have been based on the linear growth rate of the Rayleigh-Taylor instability, which is the genesis of the intermediate-scale irregularities that cause scintillations on trans-ionospheric VHF and higher-frequency radio signals. In many studies, some of the ionospheric parameters that appear in the linear growth rate of the Rayleigh-Taylor instability, γ_{RT}, given in Equation (1), have thus been estimated from ionospheric observations to show their relevance to the prediction of occurrence of scintillations. A lack of information about the thermospheric contributions to γ_{RT} led to the use of coupled thermosphere-ionosphere models, such as TIEGCM (Thermosphere-Ionosphere-Electrodynamics General Circulation Model) for estimation of γ_{RT}, which was considered as the basis for prediction of post-sunset low-latitude scintillations [21, 22]. However, it is clear that prediction of the occurrence of scintillations at off-equatorial latitudes, particularly in the equatorial-ionization-anomaly region, requires knowledge of the nonlinear development of the Rayleigh-Taylor instability, during which phase the equatorial plasma bubbles actually rise to the topside of the equatorial F layer and become structured. These irregularities then map along the geomagnetic field lines to the F-layer peak regions at different off-equatorial latitudes, depending on their height over the dip equator. Understanding this process and its dependence on background parameters calls for three-dimensional simulations of the nonlinear development of the Rayleigh-Taylor instability. Carrying out such simulations using realistic ambient conditions is a big challenge, because the background itself is dynamic [30-32]. Furthermore, until recently the spatial resolution achieved in such simulations was not adequate to study intermediate-scale irregularities involved in giving rise to ionospheric scintillations. For the first time, a sub-kilometer resolution was achieved with the high-resolution-bubble (HIRB) model [23], but the problem of simulating equatorial plasma bubble development in an approximately realistic background ionosphere and thermosphere remains.

As discussed in Sections 5 and 7, the two most important attributes of the irregularities that determine the latitudinal extent and strength of the scintillations are the maximum height attained by the equatorial plasma bubbles as they rise over the dip equator and the spectrum of the intermediate-scale irregularities that develop within the equatorial plasma bubbles at different heights above the dip equator and subsequently map down to off-equatorial latitudes. In the absence of inputs from realistic three-dimensional simulations of the development of equatorial plasma bubbles, in recent years, multi-frequency ionospheric-scintillation data from different locations, spanning the dip equatorial to beyond the equatorial-ionization-anomaly crest latitude in a particular longitude zone, have been used along with model computations of scintillation parameters to deduce the attributes of the irregularities as they develop within equatorial plasma bubbles [27, 28, 40, 48]. These results have provided information that is crucial for the prediction of low-latitude ionospheric scintillations. One of the most important results to emerge is that the long-held belief – that observation of much stronger L-band scintillations in the equatorial-ionization-anomaly region compared to the dip equatorial region is entirely due to the higher background plasma density present in the equatorial-ionization-anomaly region – has been shown to be incorrect. For the first time, crucial dependence of the strength of scintillations, as measured by the S_4 index, on the spectral index of the power-law irregularity spectrum was demonstrated [27, 28]. It was specifically shown that the observed weak amplitude scintillations on L-band signals recorded in the dip equatorial region was due to a steep intermediate-scale power-law irregularity spectrum in the equatorial F peak region. More importantly, it was concluded that if the irregularity spectrum near the peak of the F layer in the equatorial-ionization-anomaly region was as steep as it is in the equatorial F peak region, increasing the background density several fold would not produce the observed strong L-band scintillations near the crest of the equatorial-ionization-anomaly region. As far as the maximum height reached by an equatorial plasma bubble above the dip equator is concerned, the role played by the background thermospheric conditions in this aspect of the nonlinear evolution of equatorial plasma bubbles has been brought out in a recent study of the latitudinal distribution of scintillations due to equatorial plasma bubble irregularities that develop under different background thermospheric conditions when ambient ionospheric conditions are nearly the same [48]. These recent findings undoubtedly make the prediction of low-latitude scintillations more complicated. However, without these critical inputs, attempts to predict scintillations – particularly in the most problematic region near the equatorial-ionization-anomaly crest – based on only the linear growth rate of the Rayleigh-Taylor instability in the dip equatorial region are going to be futile from a practical point of view. The recent results clearly indicate the features that must be explored in the future using high-resolution three-dimensional models of equatorial plasma bubble development under different background conditions, to take the prediction of low-latitude scintillations closer to reality.

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Nonlinear Precursor Waves from a Moving Charged Object in a Plasma

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Abstract

A charged object moving at supersonic speed in a plasma not only creates the familiar Mach cone structure in its wake, but can also give rise to nonlinear wave excitations ahead of it. While wake structures that occur in the tail region of a moving object have been widely studied in the past, the existence and nature of nonlinear collective excitations occurring in front of the moving object – the fore-wake region – have remained a relatively unexplored area of investigation in plasmas. A consolidated account of recent findings on this phenomenon based on experimental studies, theoretical modeling, as well as fluid simulation and molecular dynamic investigations is presented. The excitation and propagation characteristics of electrostatic structures in the form of precursor solitons and dispersive shock waves are described, and their extension to electromagnetic waves are discussed. The relevance of such structures in gaining understanding of wave excitations occurring during the interaction of the solar wind with the Earth and moon, and some possible practical applications of such precursors, e.g., in the detection of charged space debris in the ionosphere, are also pointed out.

1. Introduction

We are all familiar with wake structures or Mach cones that arise behind an object moving in a fluid. They can be seen as trails left by speeding boats, or felt as shock structures behind aircraft moving at supersonic speeds. A less-familiar phenomenon, but one that has been widely studied in hydrodynamics, is the occurrence of wake structures in front of the moving object. These can occur when the object moves faster than a "critical" speed in the medium, such as the linear sound velocity or the characteristic phase velocity of some normal mode of the system. The study of such fore-wake structures in the upstream region of a fast-moving boat has a long history in ship hydrodynamics, going back to the mid-thirties [1, 2]. These early experiments, and subsequent experiments [3-5] carried out with model ships, revealed that in a channel of finite width and depth, a steadily advancing ship can radiate wave pulses that propagate faster than the ship's speed. These were later identified to be solitons [6], and a large number of studies in subsequent years yielded a better physical understanding of this phenomenon, and also provided a mathematical framework for their description [7, 8].

The formation of these soliton structures can be understood in terms of a simple physical picture. As the ship pushes through the water, it creates a pile-up of the water mass in front of it. If the ship's speed is sub-critical, then the pile-up can disperse away by linear wave propagation, giving rise to the familiar wake structure. However, if the ship's speed is super-critical, then the accumulated mass cannot disperse away fast enough and it keeps building up. When the build up is large enough for nonlinear effects to become important, it can lead to the formation of solitons, which can then move away at a speed faster than the ship's speed. The main features of this phenomenon are described very well by simple mathematical models based on a driven Korteweg de Vries (KdV) equation, or a driven Boussinesque equation [9-11].

The fluid model has been successfully and widely employed in plasmas to study low-frequency phenomena such as ion-acoustic waves, as well as their nonlinear evolution into solitons. Wakes and shocks in plasmas are other phenomena that are a direct analog of similar formations in fluid dynamics. In principle, one can thus expect fore-wake excitations that have been found in fluids to also occur in plasmas when a charged object moves through the plasma at a speed greater than a characteristic collective-mode phase velocity of the plasma. While conventional trailing wake structures behind moving charged objects have been seen and extensively studied [12-16], the topic of fore-wake excitations has remained a relatively unexplored topic in plasma physics [17-19]. This is surprising, considering the widespread use of fluid models in plasma physics, and the large attention paid to

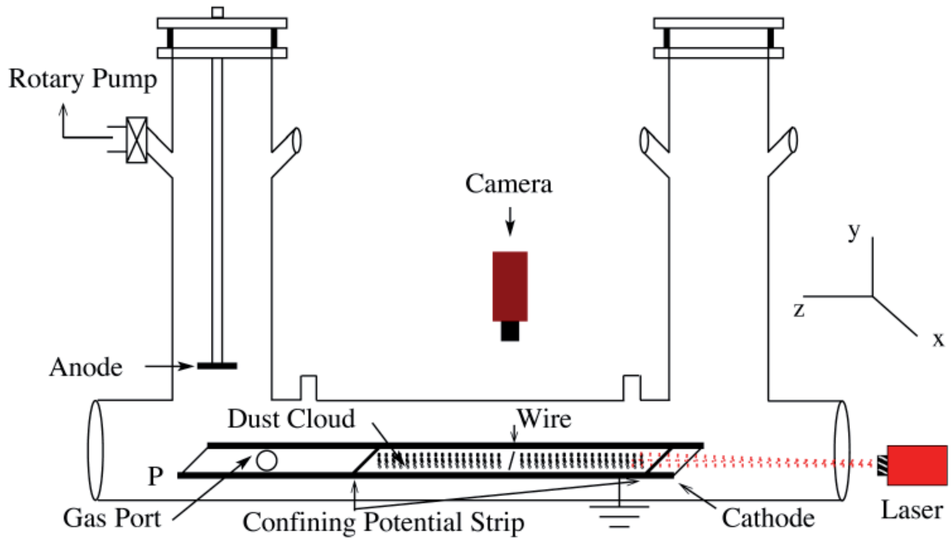

Figure 1. A schematic diagram of the dusty plasma experiment to detect fore-wake excitations due to the dust fluid flowing over a charged obstacle (from [20]).

solitons and the KdV equation. Over the past few years, a systematic investigation of electrostatic fore-wake excitations in plasmas has been carried out at the Institute for Plasma Research (IPR), Gandhinagar, through a series of studies encompassing experiments, analytic models, fluid simulations, and molecular dynamic simulations [18, 20-22]. This work is being further extended to include fluid simulations and laboratory studies of electromagnetic emissions in collaboration with scientists at the Naval Research Laboratory, USA. In this paper, which is based on my keynote lecture delivered at the URSI AP-RASC 2019, New Delhi, I present a consolidated account of this past work at IPR, as well as a description of the current and future directions of research on this topic.

The paper is organized as follows. Section 2 describes the first laboratory experimental results establishing the existence of precursor solitons in a flowing dusty plasma that was carried out at IPR. Analytic interpretation for the experimental results using the forced KdV (fKdV) model is provided in Section 3. The next two sections describe investigations of this phenomenon using full fluid simulations that go beyond the fKdV model (Section 4), and molecular dynamic simulations that take a kinetic approach (Section 5). The final section, Section 6, discusses future directions of research, including electromagnetic emissions, possible manifestations of fore-wake excitations in space plasmas, and the potential applications of these stimulated emissions in practical situations.

2. Laboratory Experimental Results

To look for evidence of fore-wake excitations in plasmas, Jaiswal et al. [20] carried out an experiment in a dusty plasma medium. The choice of a dusty plasma was primarily due to the ease of diagnosing such plasmas using well-established and non-perturbative visual techniques. Since such excitations depend on the relative motion between the object and the fluid, one can choose to move either one. For the laboratory experiment, it was convenient to make the dusty plasma flow over a charged obstacle, instead of having a charged object move inside the medium. Accordingly, the experiments were carried out in a specially constructed table-top device that had a facility to create a controlled flow of the dusty plasma. A schematic diagram of the device is shown in Figure 1, with more details available in [23]. A dusty plasma, consisting of micron-sized kaolin particles levitated above a rectangular grounded cathode tray, was created in the background of a dc glow-discharge Argon plasma. A grounded copper wire, placed 1 cm above the tray, provided an electrostatic (sheath) potential hill. Initially, the dust cloud was trapped between the potential hill of the wire and the sheath potential, above a stainless steel strip placed on the cathode to the right of the wire. The dust cloud was then made to flow over the potential hill by suddenly lowering its height through a change in the wire's applied voltage. The dust's fluid velocity, measured from video images using a standard particle image velocimetry (PIV) tool [24], was seen to quickly attain an asymptotically constant value due to friction arising from collisions with neutrals. The dust velocity, v, was controlled by varying the lowered height of the potential hill. A number of experimental runs were made to represent subsonic ($v < v_{DAW}$) and supersonic ($v > v_{DAW}$) flows, where v_{DAW} represents the linear phase speed of the dust acoustic wave (DAW). The dust acoustic wave's speed was estimated from independent measurements of the dust-cloud parameters, and found to be close to ~ 2.4 cm/s .

It was found that subsonic dust-flow velocities gave rise to wake-field structures to the left side of the wire that were seen to travel in the direction opposite to the flow.

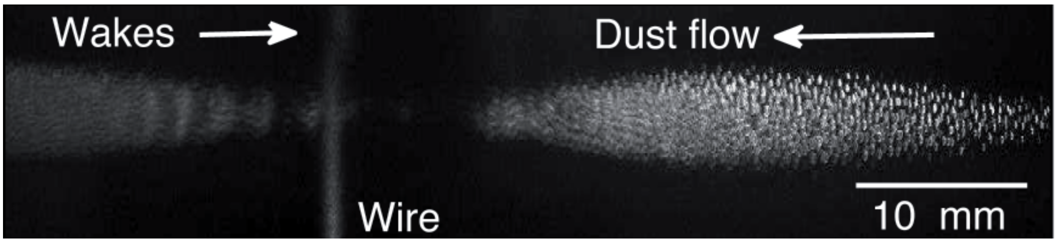

Figure 2. The generation of wakes due to the subsonic flow of the dust fluid over the wire (from [20]).

In the frame of the fluid, one can think of the potential hill (the charged object) to be moving from right to left, and hence the wake fields were in the downstream region. The Doppler-shifted velocity of the wake was taken to be $U - v_{wm}$, where U is the dust flow's velocity, and v_{wm} is the measured velocity of the wake fronts. A snapshot of a subsonic flow case is shown in Figure 1 for $U \approx 1.8$ cm/sec and $v_{wm} \approx -0.5$ cm/sec. These fronts traveled at a speed of $U - v_{wm} \approx 2.30$ cm/sec, which was close to the phase velocity of the linear dust acoustic waves.

The results changed dramatically when the flow was made supersonic. As shown in Figure 2, it was found that apart from the wake fields to the left of the wire, large solitary wave structures emerged to the right of the wire that traveled in the direction opposite to the flow. In the frame of the fluid, these solitary pulses were thus moving in the upstream direction as precursor excitations. The dust flow's velocity in Figure 2 was $U \approx 2.65$ cm/sec. The measured velocity of these structures was $v_{sm} \approx -1.5$ cm/sec. Their actual speed, after taking account of the flow, was $v_s = U + v_{sm} \approx 4.15$ cm/sec. This was about 1.6 times the dust's acoustic wave speed. The experimental runs made over several different flow velocities led to the following empirical observations [25]:

- The excitation of the fore-wake pulses happened only when the dust flow was supersonic.
- Once excited, these solitary pulses continued to propagate at their nonlinear speed, which was faster than the flow speed.
- The speed of the pulses depended on the amplitude of the pulses, becoming faster for larger amplitudes.
- These precursor pulses were emitted at regular intervals and after a transient period of growth, attained a saturated amplitude.

All of the above experimental findings taken together helped establish the existence of fore-wake excitations in plasmas. The characteristic features of the precursor pulses were also seen to be close to the typical properties of KdV solitons. The regularity of their emission appeared to be in accord with predictions of past hydrodynamic-model equations based on the forced KdV equation. These experimental findings were then further subjected to theoretical comparisons with model solutions of the fKdV equation, discussed in the next section. The fundamental concept of fore-wake excitations itself was tested through fluid and kinetic simulations, as discussed in Sections 4 and 5, respectively.

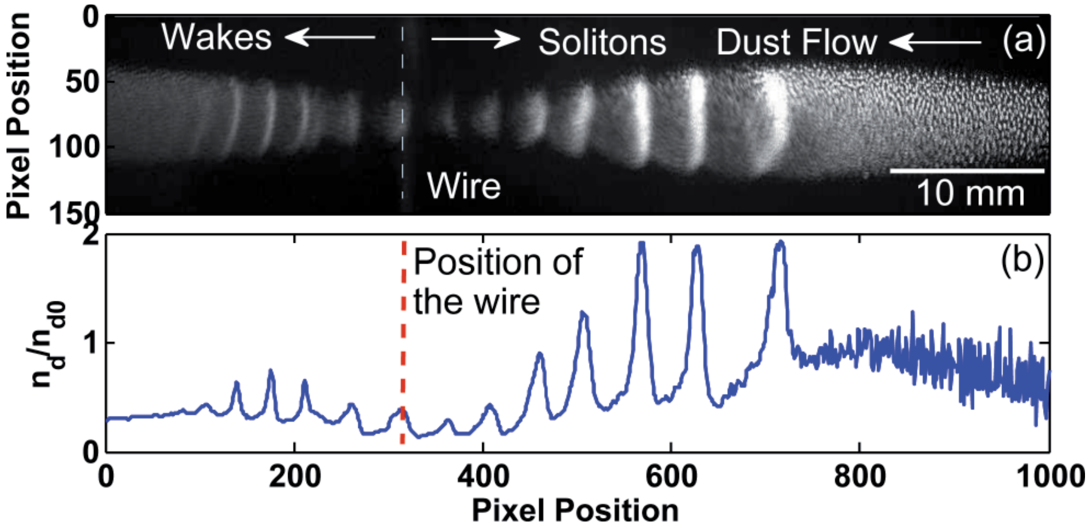

Figure 3. (a) An experimental image of the excited precursor solitons and small amplitude wakes. (b) The intensity profile of Figure 3a (from [20]).

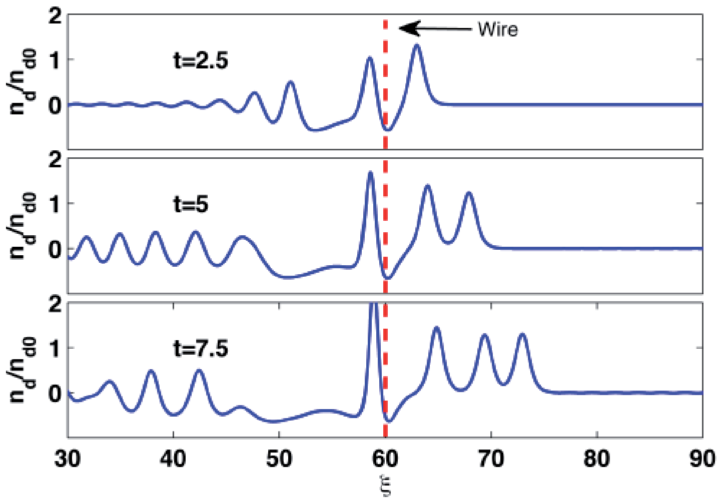

Figure 4. The time evolution of precursor solitons and wakes obtained from a numerical solution of the fKdV Equation (1) (from [20]).

3. The Forced KdV Model

For an analytic interpretation of the above-mentioned experimental results, the observations were compared to solutions of a model-forced KdV equation. Such an equation, derived for a charged object moving through a dusty plasma, is given by [20]

$$\frac{\partial n_{d1}}{\partial t} + A n_{d1} \frac{\partial n_{d1}}{\partial \xi} + \frac{1}{2} \frac{\partial^3 n_{d1}}{\partial \xi^3} = \frac{1}{2} \frac{\partial S_2}{\partial \xi}, \tag{1}$$

where n_{d1} is the perturbed dust density, normalized to the equilibrium dust density, and $\xi = (z - u_{ph} t)$ is the coordinate in the wave frame moving at phase velocity u_{ph}, normalized to the dust's acoustic speed. The spatial coordinate, z, is normalized by the Debye length (λ_d), and time is made dimensionless by the dust plasma frequency (ω_{pd}). The left-hand side of Equation (1) is the usual KdV equation describing the evolution of finite-amplitude nonlinear waves in a dusty plasma, with the coefficient A being a constant that is dependent on the background plasma as well as dusty plasma properties [25], and which for the present experimental parameters was approximately 6.2.

The term $S_2(\xi + Ft)$, on the right-hand side of Equation (1), represents a charged source term moving at a velocity v_d with $F = 1 - v_d$. If the source is held stationary (as in the experiment), then the dusty plasma moves in the opposite direction with speed $-v_d$. Figure 4 shows typical time-evolution plots of n_{d1} for $v_d > 1$ from a numerical solution of Equation (1) with a Gaussian source term, S_2, used to model the wire-generated potential hill. To compare with the experimental observations, the solutions were plotted in the frame of the moving source, which was now stationary at the point marked by the dashed line. As could be seen, the source periodically excited soliton pulses ahead of its path that traveled away at a faster speed. Weaker excitations, consisting of wakes, were seen to emerge in the downstream direction. The fKdV model was thus found to provide a consistent qualitative description of the experimental observations.

Since one did not have a precise knowledge of the exact shape and size of the wire-generated potential hill, one could not make a more-quantitative comparison of the pulse amplitudes with the numerical results. However, to further ascertain the validity of the fKdV model, two quantitative tests were carried out. The first test was to confirm whether the emitted pulses were indeed solitons, and consisted of examining the product of their amplitudes with the square of their width. For a soliton solution, this quantity should be a constant [26]. Figure 5a shows a plot of the measured value of this product quantity for the solitonic structures of different sizes observed in the experiments, and this was seen to be nearly a constant (of value close to unity). The fKdV model

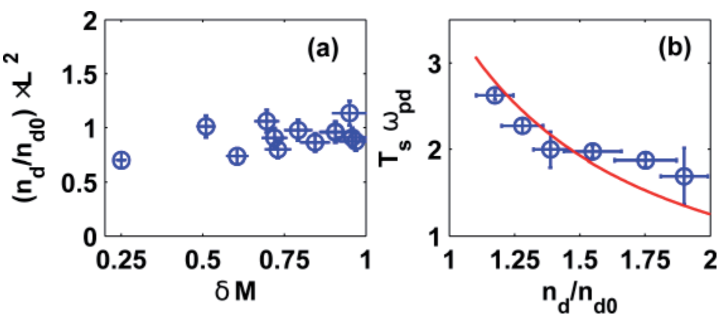

Figure 5. The variation of (a) the soliton parameter (amplitude × width²) with excess Mach number $\delta M = M - 1$, where the Mach number, M, was normalized to the dust acoustic wave speed. (b) The time interval between the generation of two fully developed solitons with the amplitude. The solid line in Figure 5b is a plot of the curve $T_s \omega_{pd} = \alpha / (n_d / n_{d0})^{3/2}$ where $\alpha = 3.54$ (from [20]).

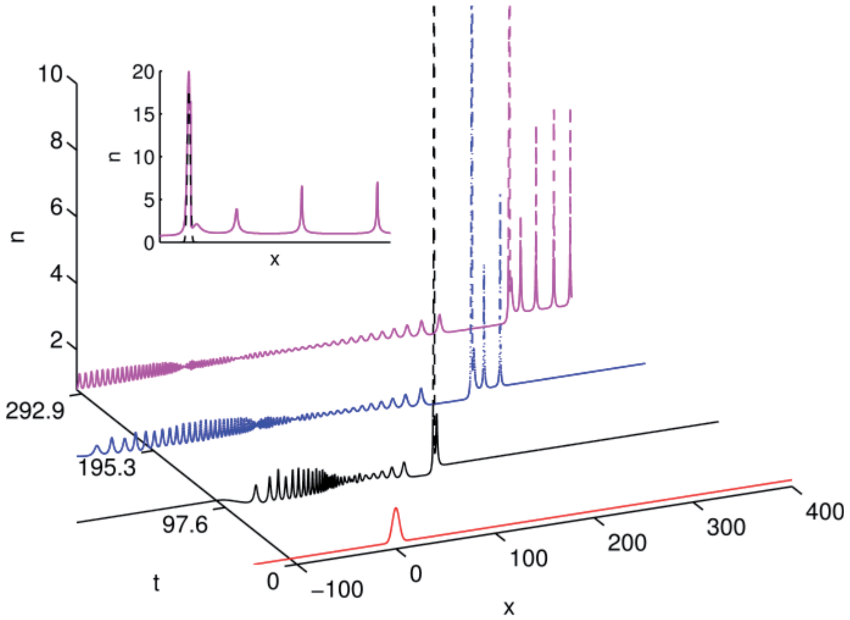

Figure 6. The formation and evolution of precursor solitons due to a charged source moving at $v_d = 1.15$. The density profile of the source was $S(\zeta) = A_m \exp\left[-(\zeta/\delta)^2\right]$ with $A_m = 18$ and $\delta = 0.488$. The inset shows the evolution of the initial perturbation along with the evolving source, and shows the solitons moving ahead of the source in the medium (figure reproduced from [21]).

also predicts a scaling law for the inter-solitonic intervals, namely $T_s \propto H^{-3/2}$, where T_s is the interval between the generation of the solitons, and H is the amplitude of the soliton [10]. Figure 5b shows a plot of the experimentally observed time intervals (normalized to the dust plasma frequency) against the soliton amplitudes (n_{d1}/n_{d0}). The time intervals were seen to monotonically decrease with increasing amplitudes of the solitons. The solid curve is an analytic plot of the function $T_s\omega_{pd} = \alpha/(n_d/n_{d0})^{3/2}$ with $\omega_{pd} \approx 30$ Hz, $\alpha = 3.54$, and serves as a visual aid to discern the trend in the data points.

It should be mentioned that the fKdV model, Equation (1), ignores dissipative effects. In an experimental situation, the energy of the dust acoustic wave soliton would decay as $e^{-\nu_{dn}t}$ [27, 28], where ν_{dn} is the dust neutral collision rate. In the experiments, ν_{dn} was estimated to be $\approx 9\ \mathrm{s}^{-1}$. For a soliton speed of $v_s \sim 4.15$ cm/sec, the damping length was thus approximately $3v_s/2\nu_{dn} \sim 7$ mm, which was about nine times larger than the width ($\Delta \sim 0.8$ mm) of the soliton. The emitted pulse was observed to develop into a soliton over an average distance of about 5 mm, and its average propagation length without significant decay was about 9.5 mm. To a good approximation, it was hence possible to neglect dissipative contributions and to provide an analytic interpretation of the experimental results with the help of the fKdV model.

4. Fluid Simulations

As is well known, like the KdV equation, the fKdV model equation is also derived by a perturbative expansion method under the approximation of weak nonlinearity and weak dispersion. This raises the question of whether the fore-wake excitations are limited to such a physical limit and can only occur within the constraints of the fKdV model. To explore this question, Tiwari et al. [21] carried out numerical simulations using the entire set of fluid equations and with an arbitrary moving driving term providing a charge-density source in the Poisson equation. To simplify the analysis, a cold electron-ion plasma model was adopted, and only one-dimensional nonlinear ion-acoustic waves were considered in the following set of equations:

$$\frac{\partial n}{\partial t} + \frac{\partial (nu)}{\partial x} = 0\,, \tag{2}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{\partial \phi}{\partial x} = 0\,, \tag{3}$$

$$\frac{\partial^2 \phi}{\partial x^2} = e^{\phi} - n + S(x - v_d t)\,. \tag{4}$$

Here, n, u are the density and velocity of the ion fluid, respectively, and ϕ is the electrostatic potential. Equation (2) is the ion continuity equation, Equation (3) is the ion momentum equation, and Equation (4) is Poisson's equation, where S is the additional charge density arising from the moving charged source. The above dimensionless equations have the following normalizations:

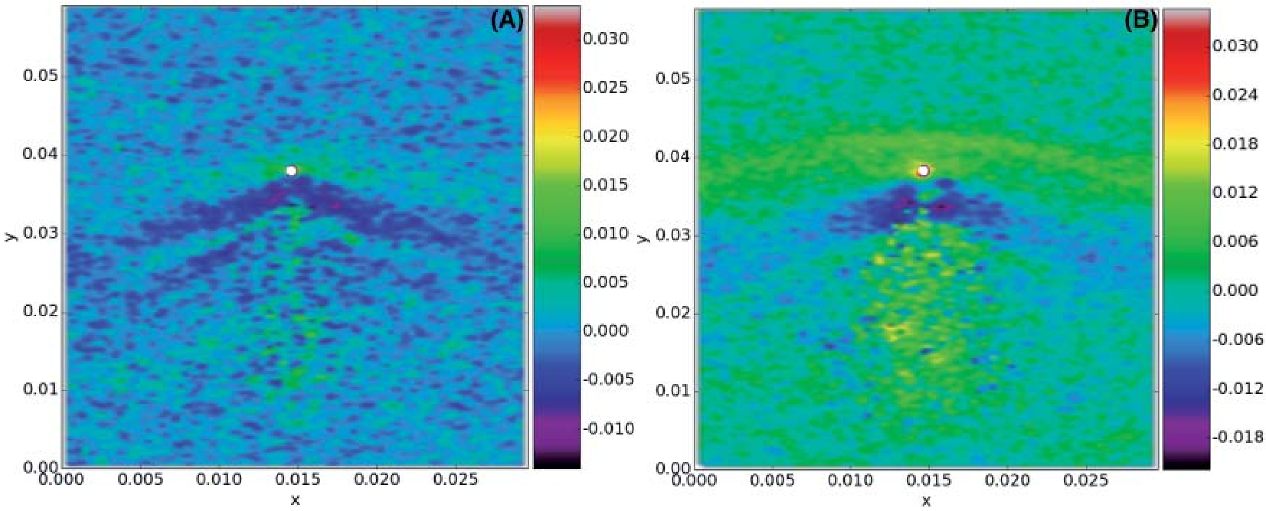

Figure 7. (A) The formation of a Mach cone for a charged projectile with $z_p = z_d$ streaming at $M \approx 1.1$. (B) When the projectile charge was increased to $z_p = 10z_d$, nonlinear precursor pulses were excited in the fore-wake region. The white disc symbol marks the position of the projectile particle. The system dimensions were $l_x = 125a$ and $l_y = 250a$, with $\Gamma = 20$, and the other simulation parameters were as mentioned in the text (from [22]).

$$x \to x/\lambda_{De},$$

$$t \to \frac{c_s}{\lambda_{De}} t,$$

$$n \to \frac{n}{n_0},$$

$$u \to \frac{u}{c_s},$$

$$\phi \to \frac{e\phi}{k_B T_e},$$

where λ_{De} is the electron Debye length, c_s is the ion acoustic velocity, T_e is the electron temperature, k_B is the Boltzmann constant, e is the electronic charge, and the ions are treated as being cold ($T_i = 0$). The results of a numerical solution of Equations (2)-(4), with a Gaussian source $S(x) = A_m exp\left(-x^2/\delta^2\right)$ moving at a supersonic speed of $v_d = 1.15$, and with $A_m = 18$ and $\delta = 0.488$, are shown in Figure 6. As could be seen, the solution was in the form of wake structures in the downstream region of the source, and fore-wakes in the form of spiky pulses. These pulses traveled faster than the moving source and moved away from it, much like the fKdV pulses. It was found that these precursors were emitted for a range of velocities, v_d, and ceased to exist if $v_d > 1.5$. This behavior is analogous to what has been observed for the fKdV, but in this case, it emerged from the full set of fluid equations. It is therefore valid for arbitrary amplitude perturbations, thereby establishing the generic nature of these fore-wake excitations.

5. Molecular Dynamic Simulations

The next step was to go beyond the fluid model and look at such excitations from a kinetic viewpoint, and to investigate the phenomenon using a particle-based approach. For this, Tiwari et al. [22] went back to a dusty plasma system, and carried out a set of molecular dynamic simulations in a two-dimensional Yukawa system in which charged projectiles were made to travel at various velocities. Depending upon the speed of a projectile and the amount of charge on it, one observed the excitation of precursor solitons or dispersive shock waves with propagation characteristics close to those predicted by earlier fluid formulations. The individual particle dynamics helped provide a detailed picture of the underlying mechanisms at play in the formation of the precursors, such as the initial density accumulation in front of the projectile, the corresponding depletion of matter at the rear, and the dynamical evolution characteristics of the distribution function. The simulations also showed that the background density, the Coulomb coupling parameter, and the amount of dissipation arising from neutral collisions can have significant impacts on the excitation and dynamics of the precursors. Some typical results are now discussed.

In the first set of simulations, a single point projectile, with a charge $Q_p = z_p e$, was made to travel with various Mach numbers, M. The characteristics of the medium were parametrized by the magnitude of the Coulomb coupling constant, $\Gamma = Q^2/\left(4\pi\varepsilon_0 a k_B T_d\right)$ (where k_B is the Boltzmann constant, a is the inter-particle distance, and T_d is the dust temperature). Γ is a measure of the strong

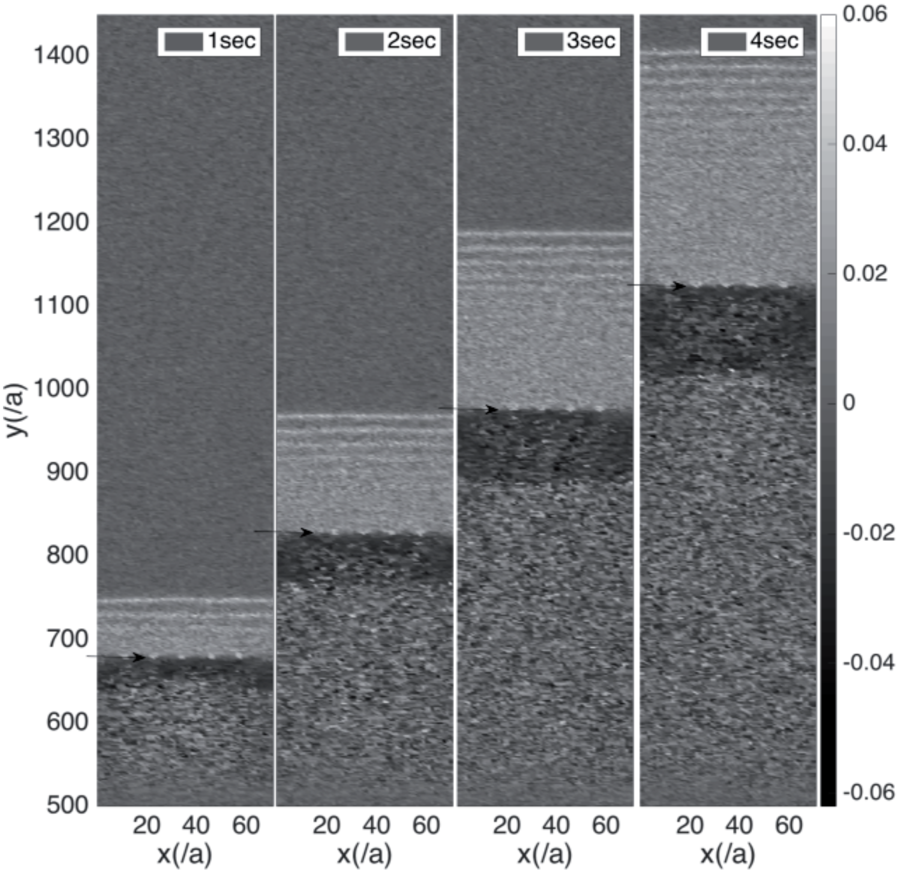

Figure 8. A particle-density map showing the formation and evolution of precursor excitations due to a moving array of five charged particles, each with $z_p = 10z_d$, and moving at $M \approx 1.1$. The source position is marked with an arrow in each subplot. The dark region behind the source was the wake generated by the moving source. The system dimensions were $l_x = 70a$ and $l_y = 1770a$, and $\Gamma = 17$ (from [22]).

coupling effects in the medium, signifying the strength of the dust-dust correlations. Simulation results for a typical run with $\Gamma = 20$, $M = 1.1$, and two different values of z_p are shown in Figure 7. When the charge on the projectile was the same as the charge on the medium particles, i.e., $z_p = z_d$, the impulse to the medium was rather weak, and one only observed the formation of a Mach cone trailing the projectile. However, when $z_p = 10z_d$, one observed the formation of nonlinear precursor pulses traveling ahead of the projectile.

To simulate conditions close to the experiments and to remain as near as possible to the one-dimensional fluid results, a set of five charged particles arranged in a horizontal array (to mimic a line source) were made to move in the Yukawa system at a supersonic speed. The results, displayed in Figure 8, showed a series of one-dimensional precursor pulses in the fore-wake region, quite similar to the experimental observations and the fluid results discussed before. The structure of these pulses could be more clearly seen from one-dimensional images of the two-dimensional density patterns (created by averaging over the x direction) that are shown in Figure 9. They showed two distinct types of excitations, depending upon the speed of the projectile. The image in the left panel (A) was for $M \approx 1.01$, and that of the right panel (B) was for $M \approx 1.1$. These one-dimensional snapshots had some interesting features. For example, they showed the accumulation of the density in front of the moving source, and the depletion of density immediately behind it, revealing the dynamics of the formation of the precursor pulse. The early time nature of the pulse structure depended on the speed of the projectile. When the projectile speed was slightly above the sound speed, there was sufficient time for the density build-up to form a soliton and move away, as shown in panel (A). When the speed of the projectile was very high, the density build-up was so rapid that it did not permit the exact balance of dispersion with nonlinear steepening, and instead of a soliton one ended up with a non-stationary dispersive shock wave (DSW), as seen in panel (B). With time, the oscillation amplitudes of the dispersive shock wave increased and the distance between them increased, eventually leading to a train of soliton pulses. The experimental findings reported in [20] belong to the category of relatively slower-speed projectiles, and hence consisted of precursor solitons.

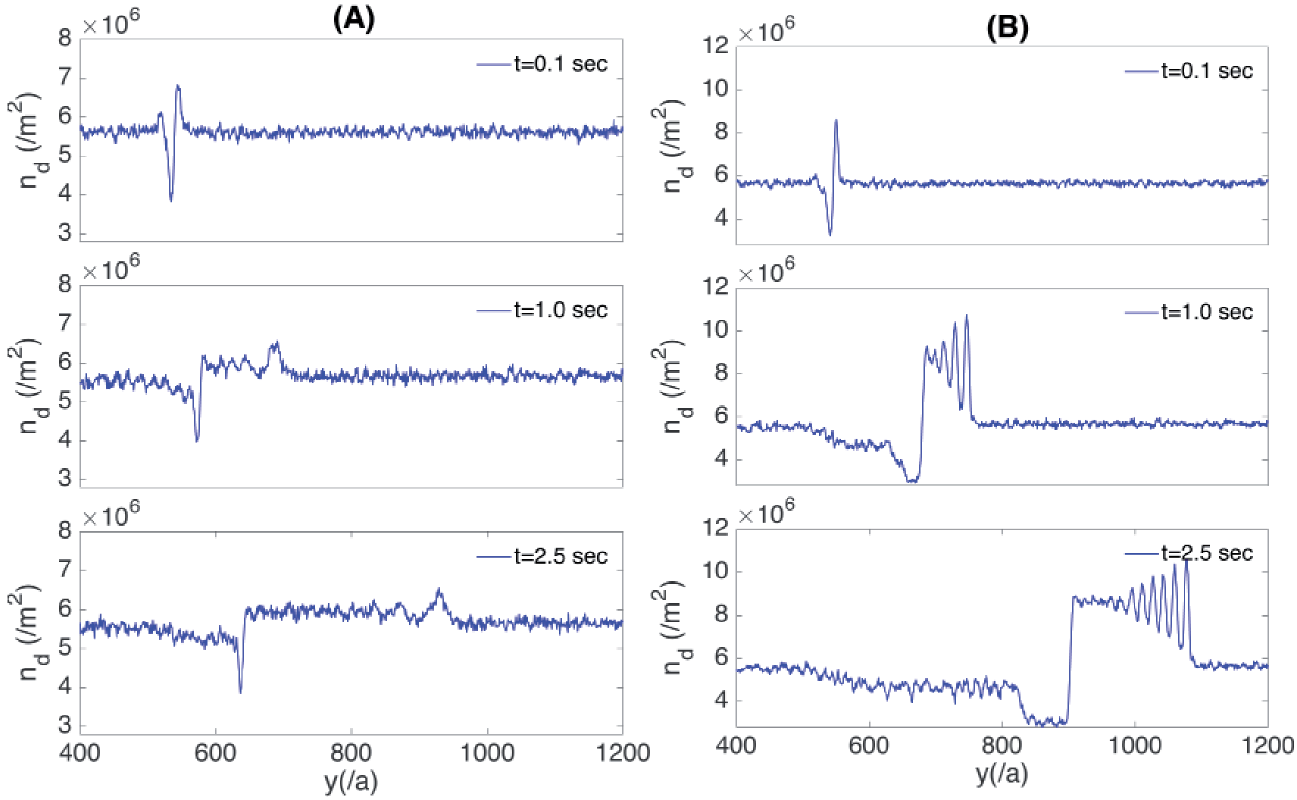

Figure 9. One-dimensional pictures of density-profile evolution at time steps $t = (0.1, 1.0, 2.5)$ when a charged array of particles streamed through the medium. The array-streaming velocities were $M \approx 1.01$ and $M \approx 1.1$ for the subplots (A) and (B), respectively. All other simulation parameters were the same as in Figure 7 (from [22]).

6. Discussion and Future Work

From the results presented in the previous sections – encompassing laboratory experimental results, numerical solutions of fluid models of plasmas, and molecular-dynamic simulations of Yukawa fluids – I believe a strong case can be made in favor of the existence of precursor solitons in plasmas. The conditions for their excitation appear in general to be very similar to those of their fluid analogs. Such conditions are not uncommon in nature, and therefore one should look for their occurrence in such situations. The solar wind (which has supersonic as well as super Alfvenic components) interacting with the Earth or the moon is one such situation where the fast streaming plasma component charges the Earth as well as flows past it. In the frame of the solar wind, the Earth (or moon) can be considered to be a charged object moving in the plasma, and one could have precursor nonlinear structures in the upstream direction, i.e., moving towards the sun. While such structures have not been definitively identified or even looked for to date, there is some evidence of fore-wake activity in the solar-wind region, such as satellite observations of ultra-low-frequency (ULF) fore-wake activity in the region upstream of the lunar wake [29, 30], and also low-frequency whistler fluctuations in the upstream region [31, 32] of the Earth's bow-shock.

Another area where fore-wake excitations can occur are in front of orbiting satellites or orbiting space debris in the ionospheric region. These objects, which can get charged due to the plasma environment or other sources (such as solar radiation or energetic particle bombardment), can also in principle excite nonlinear plasma-wave structures in their fore-wake region. In the case of small-sized space debris objects, detection of these precursor waves can provide a means of tracking the debris objects and monitoring their orbits, as suggested in [18]. The basic idea is that these multiple precursor solitons (or dispersive shocks) can create a cloud of plasma irregularity with a dimension larger than the debris. This can effectively increase the radar cross section, making it easier to detect small debris that are optically difficult to resolve. Recognition of such debris-generated irregularities using ground- or space-based techniques can thus provide a novel method of detecting sub-centimeter-sized objects that are otherwise difficult to track using optical methods.

Our discussions and research findings have so far been restricted to electrostatic fore-wake excitations in the form of low-frequency wave structures arising from ion-acoustic or dust-acoustic waves. In principle, a moving charge source also constitutes a current source, and hence it can give rise to electromagnetic excitations. For example, in a magnetized plasma, one can think of precursor magneto-sonic solitons or Alfvenic solitons. The conditions for excitation of such electromagnetic solitons have recently been worked out using simple fluid models. For magneto-sonic solitons propagating perpendicular to an ambient magnetic field, the dynamics are seen to be, once again, well captured by a corresponding fKdV equation [33]. Further consolidation of these results using numerical solutions of two-fluid plasma models and first-principles particle-in-cell (PIC) simulations are presently in progress. One of the striking differences between the electrostatic and electromagnetic fore-wake excitations would be in the magnitude of their sizes. Typically, an electrostatic soliton has a size of the order of a few Debye lengths. In the ionospheric low-Earth-orbit (LEO) region, the soliton width would be of the order of a few centimeters. Electromagnetic solitons have widths that are typically of the order of a few skin depths. In the same LEO region, a soliton formed from a fast magneto-sonic wave would thus have a width of a few electron skin depths, which would be of the order of a few meters. A slow magneto-sonic soliton with a width span of a few ion skin depths would extend up to a few kilometers. For debris-detection applications, electromagnetic precursors with their larger footprints would thus be easier to detect and prove more useful. Electromagnetic wave structures would also last much longer compared to electrostatic waves, as the latter can be subject to strong Landau damping in the LEO region, where the electron and ion temperatures are comparable.

The subject of fore-wake excitations in plasmas is still in its infancy, and much remains to be explored and understood, both experimentally and theoretically. Excitation and characterization of precursor solitons, along the lines reported in [20] for dusty plasmas, need to be carried out in regular plasmas under varying conditions in order to establish their existence on a firmer experimental footing. Experimental evidence can also be sought in the vast database of satellite and ground-based observations on plasma flows and field fluctuations in space plasmas by looking for correlations that can establish their precursor nature. There are also exciting theoretical areas to be explored. As an example, the fKdV equation, although not completely integrable, has a rich dynamics and many novel solutions. Apart from the fast traveling precursor solitons, it also admits a soliton solution that sticks to the moving object and travels with it. Such "pinned" solitons have various shapes and sizes, and have not been experimentally or theoretically investigated a great deal. It is possible that the Earth's bow shock constitutes one such giant pinned soliton, if one looks at it from the point of view of the Earth moving through the solar wind. In a broader sense, the present findings provide a new perspective for looking at stimulated emissions arising from the interaction of a flowing plasma with stationary objects, and also open up a range of new directions of nonlinear plasma research and applications that can be fruitfully pursued in the future.

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Reducing the RCS of a MIMO Antenna Using an Angularly Stable FSS

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Abstract

A systematic design procedure for reducing the radar cross section (RCS) of a multiple-input multiple-output (MIMO) antenna is presented in this paper. The RCS reduction was achieved at 11.3 GHz, which was out-of-band compared to the antenna's working frequency of 2.18 GHz. The design flow started with developing an isolation-enhancement network for the MIMO antenna that did not disturb the RCS reduction process. An incident- and polarization-angle-insensitive frequency-selective surface (FSS) was next designed. The conventional ground plane of the MIMO antenna was replaced by an FSS array. The designed FSS was introduced in such a way that the antenna's characteristics and isolation among the antenna ports were preserved by achieving the RCS reduction of an antenna at the bandpass frequency of the FSS. The proposed FSS was angularly stable, and hence an almost constant RCS reduction was found for most of the incident angles. The final proposed low-RCS MIMO antenna was fabricated and measured to validate the simulation results.

1. Introduction

To meet the ever-growing demands of high data rates and excellent data transmission in wireless communication, multiple-input multiple-output (MIMO) technology was introduced. Single-input single-output (SISO) technology is being replaced by MIMO technology on all platforms. The Defense Advanced Research Projects Agency (DARPA) recognized the significance of using MIMO technology in defense applications for the sake of increasing the war fighter's capabilities [1]. The Wireless Networking and Communications Group (WNCG) talks about the usefulness of MIMO technology in military applications [2].

In the defense and military environment, some applications require low RCS materials. By using antennas in defense applications, the RCS will be drastically increased because the antennas are backed by a PEC ground plane. To address this problem, researchers have proposed many antenna RCS reduction techniques. These include using RCS reduction techniques based on a radar-absorbing material (RAM) [3, 4], an antenna coating [5], a frequency-selective surface (FSS) [6, 7], a metasurface [8, 9], and an artificial magnetic conductor (AMC) [10]. For applications where size matters, FSS- and metasurface-based RCS reduction techniques seem to be the most efficient, because they do not involve any extra circuitry, unlike other techniques. However, if the FSS-based RCS reduction technique is to be applied to MIMO antennas, the isolation among the antenna ports should first be addressed. The involvement of an FSS in a MIMO antenna disturbs the surface-current distribution, which in turn affects the isolation between the antenna elements [11]. A compatible isolation-enhancement network is thus needed for MIMO antennas before beginning the RCS-reduction process.

In the literature, there are various isolation-enhancement techniques for MIMO antennas. They can be divided into five major categories. These are the use of defected ground structures (DGS) [12, 13], parasitic elements [14, 15], neutralization lines [16, 17], decoupling networks [18, 19], and metamaterials [20, 21]. Among these, isolation techniques based on defected ground structures, neutralization lines, and parasitic elements disturb the surface current distribution between antenna elements to enhance the isolation between the elements. Because the involvement of an FSS in the ground plane of a MIMO antenna for RCS reduction also disturbs the surface current, those three isolation techniques are not suitable for the RCS-reduction process. A decoupling network in a MIMO antenna provides isolation between the antenna ports by not letting the surface waves propagate from one antenna element to other elements. Metamaterials utilize their bandgap nature to provide isolation among the antenna elements of a MIMO antenna. Both these isolation techniques are compatible with use in the RCS-reduction process of MIMO antenna systems.

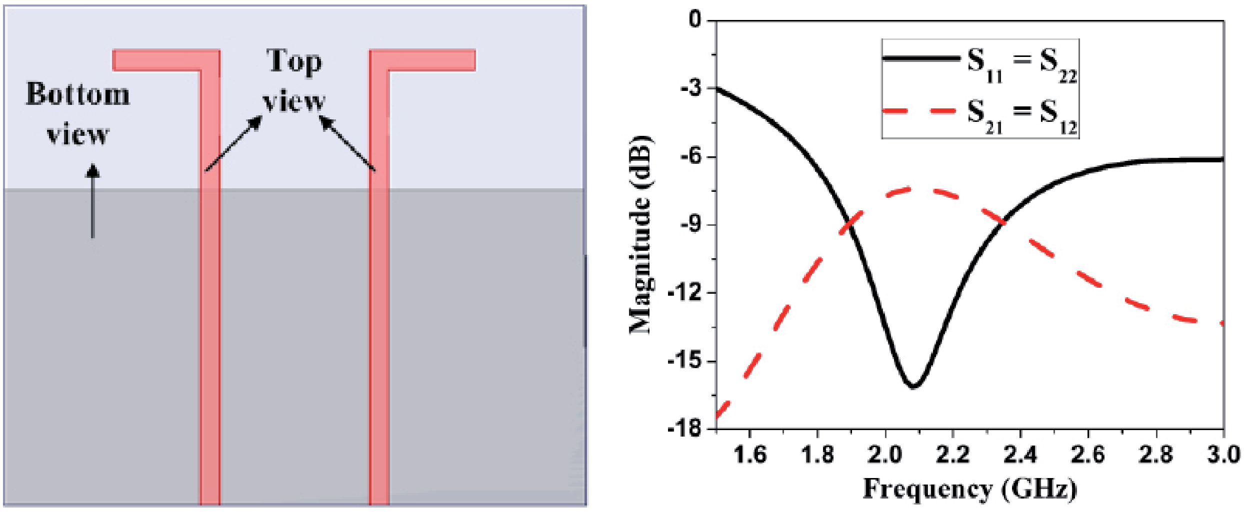

Figure 1. A simple two-port antenna: (a) the design, and its (b) *S* parameters (simulated).

In this work, we developed a filter-based decoupling network to enhance the isolation in MIMO antennas, making it suitable for the RCS-reduction process. The novelty of this paper is that the proposed isolation-enhancement circuit and RCS-reduction circuit are independent. Controlling one circuit will not affect the other. Even though FSS-based RCS-reduction techniques have been proposed in the literature, they are not insensitive to the angle of incidence. In order to provide constant RCS reduction for all the incident angles, an angularly stable FSS was developed.

2. A MIMO Antenna Design Having a Filter-Based Decoupling Network

For all the designs that are provided in this paper, the base substrate was FR4 with a thickness of 1.6 mm.

The design process started with the two-element antenna shown in Figure 1a. The two monopole antennas are shown in Figure 1a: they were closely spaced, without any decoupling network. The isolation was hence very poor in between them at the antenna's resonant frequency of 2.08 GHz, shown in Figure 1b. To enhance the isolation between the antenna elements, a decoupling network was designed at 2.08 GHz, as shown in Figure 2a. From its *S* parameters, as shown in Figure 2b, a band-stop property could be identified at 2.08 GHz.

In the next step, this band-stop filter was inserted in between the antenna elements of a two-port MIMO antenna, shown in Figure 3a. By directly inserting the decoupling network, isolation was achieved, but with the resonant frequency of the antenna shifted away from 2.08 GHz as shown in Figure 3b. To achieve both resonance and isolation at the same frequency, i.e., at 2.08 GHz, a matching network in the form of stubs was therefore used. The final proposed MIMO antenna, along with matching and decoupling networks, is shown in Figure 4a. The dimensions of the elements in Figure 4a were $a = 58$, $b = 50$, $c = 41.9$, $d = 19.5$, $e = 18.5$, $f = 15$, $g = 12.7$, $h = 12$, $i = 10.6$,

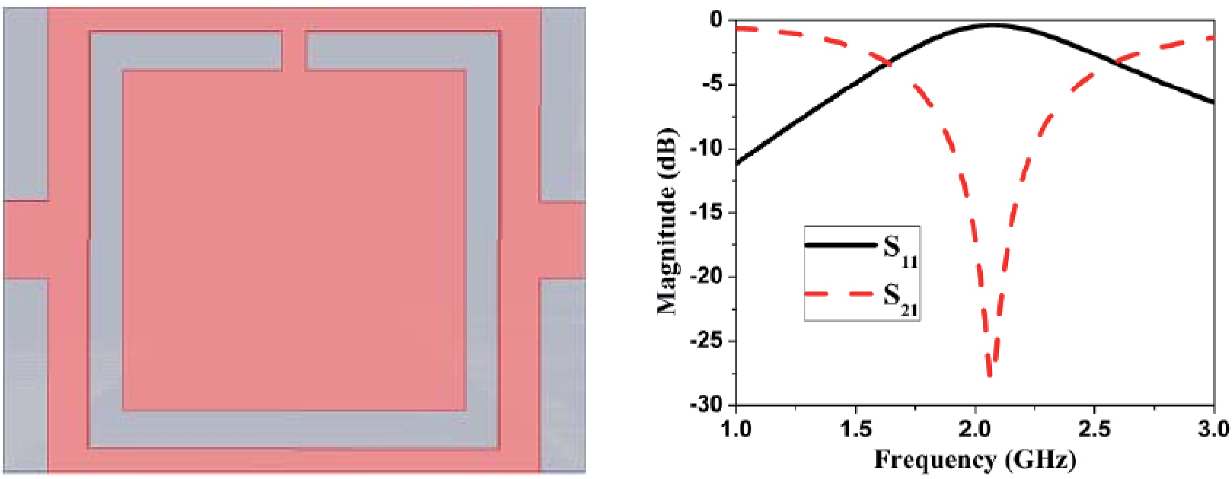

Figure 2. The decoupling network (band-stop filter): (a) the design, and its (b) *S* parameters (simulated).

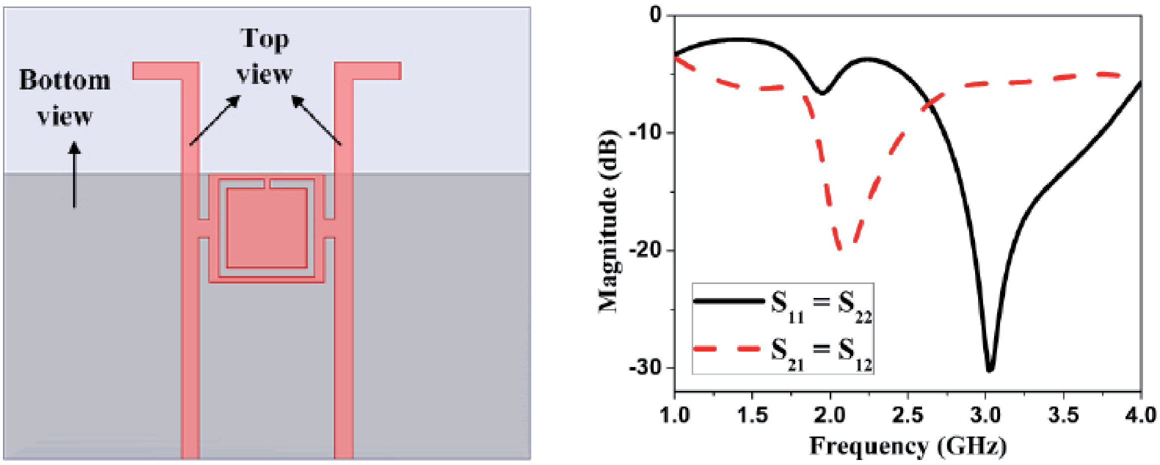

Figure 3. The two-port antenna with decoupling network: (a) design, and its (b) *S* parameters (simulated).

$j = 8.85$, $k = 7.25$, $l = 4.1$, $m = 3$, $n = 1.9$, and $o = 1$ (all in mm). From its *S*-parameter plot, shown in Figure 4b, one could observe that more than 16 dB isolation was achieved in the antenna's working band.

To get a clear idea of how the isolation was enhanced by using the decoupling network, the surface-current distribution is shown on the MIMO antenna at 1 GHz and 2.08 GHz in Figure 5. Both of the plots in Figure 5 were obtained by exciting only one port while terminating the other port with a matching impedance. From Figure 4b, at 2.08 GHz, the isolation was very high as compared to the isolation at 1 GHz. The same could be observed by looking at Figure 5. In Figure 5a, the surface current from the excitation port was not flowing towards the terminated port. In contrast, in Figure 5b, a maximum surface current was flowing. This was the reason for less isolation at 1 GHz, as shown in Figure 4b.

The fabricated MIMO antenna's top and bottom portions are shown in Figures 6a and 6b, respectively. The simulated *S* parameters were validated by measuring them, as shown in Figure 7a. Good agreement was found between measured and simulated results. The proposed MIMO antenna exhibited around 2 dBi peak gain and more than 70% radiation efficiency at the antenna's working frequency, as shown in Figure 7b. The peak gain in Figure 7b was a measured result, whereas the radiation efficiency was a simulated result. In both the *xz* and *yz* planes, the measured two-dimensional radiation patterns along with the simulated patterns are shown in Figure 8. These radiation patterns were calculated at the antenna's resonant frequency of 2.08 GHz. The given radiation patterns were obtained by exciting only one antenna element. However, because both of the antenna elements were symmetrical, similar kinds of radiation patterns with a 180° phase shift could be obtained by exciting the other antenna element. The envelope correlation coefficient (ECC) and capacity loss are important parameters for estimating MIMO performance. In this paper, both of these parameters were measured and are shown in Figure 9. In the antenna's working band, both of these MIMO parameters were within the allowable limits [22, 23]. It hence could be said that the proposed two-port antenna was a suitable candidate for MIMO applications.

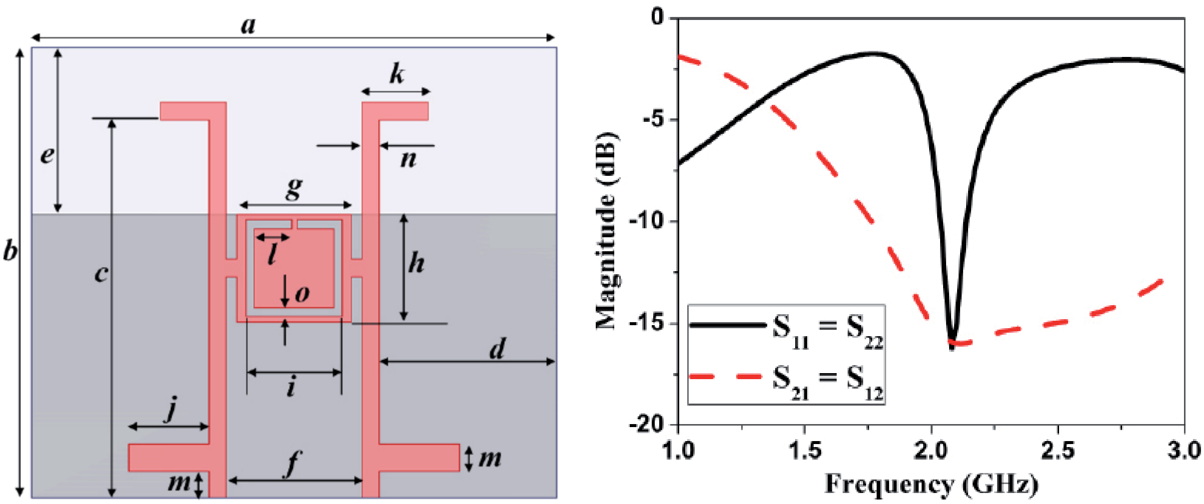

Figure 4. The proposed two-port MIMO antenna: (a) the design, and its (b) *S* parameters (simulated).

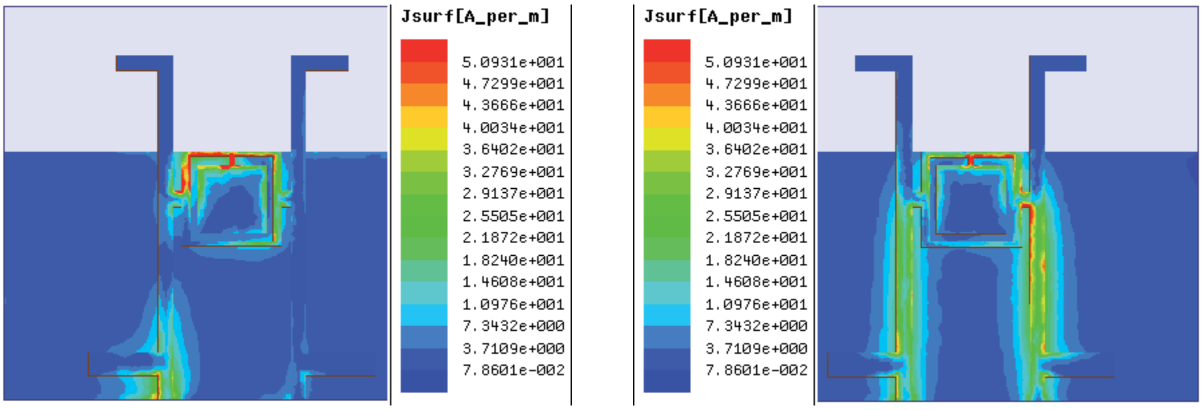

Figure 5. The surface-current distribution on the MIMO antenna at (a) 2.08 GHz and (b) 1 GHz.

3. Reducing the RCS of the MIMO Antenna

In the previous section, the design of a MIMO antenna using a filter-based decoupling network was shown. The procedure for reducing the RCS of the designed antenna is presented in this section. The first step in an RCS-reduction process is designing an FSS at a frequency where the RCS reduction of the MIMO antenna is needed. Here, two FSS designs are presented to explain the importance of an angularly stable FSS in making the RCS reduction incident-angle insensitive. The first FSS is denoted as FSS_1, and

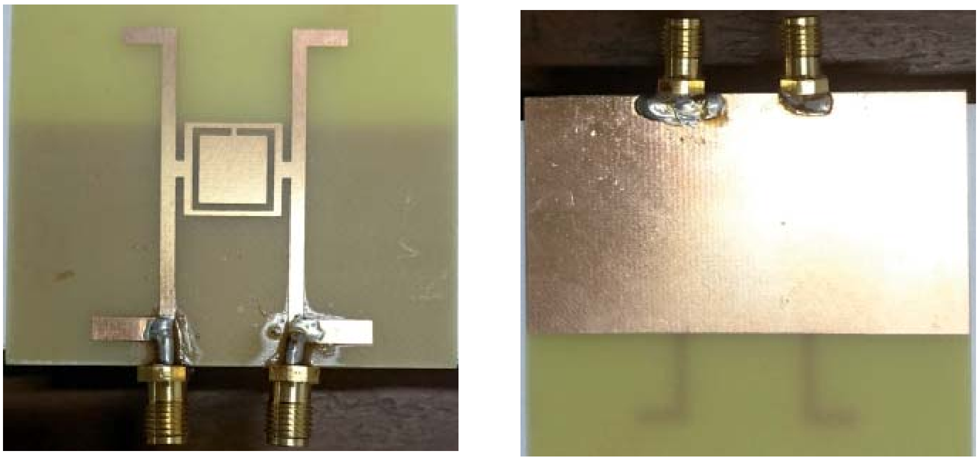

Figure 6. The (a) top and (b) bottom views of the fabricated proposed MIMO antenna.

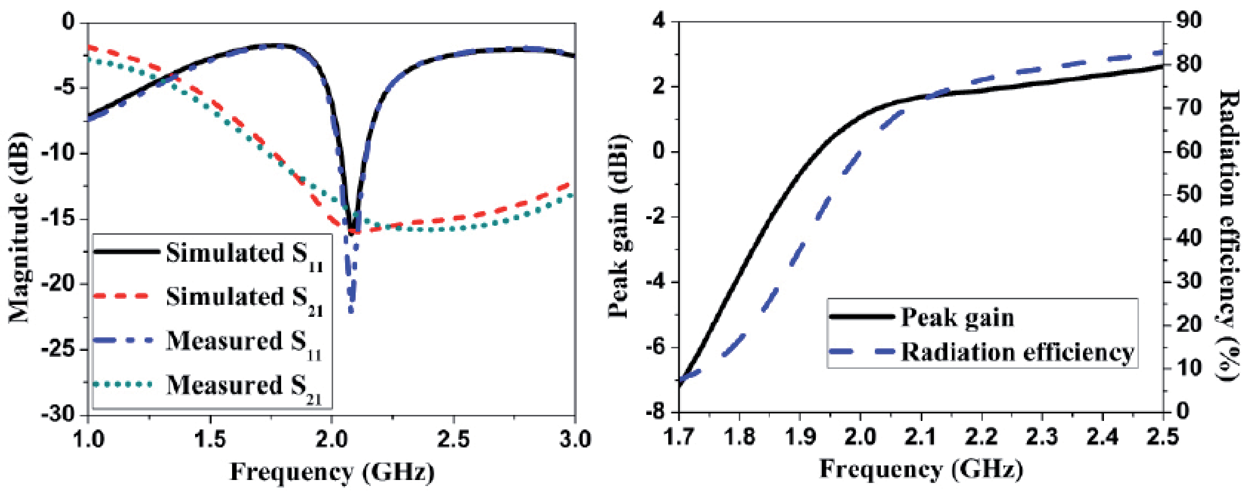

Figure 7. (a) A comparison of simulated and measured *S* parameters, and (b) the peak gain (measured) and radiation efficiency (simulated) of the antenna.

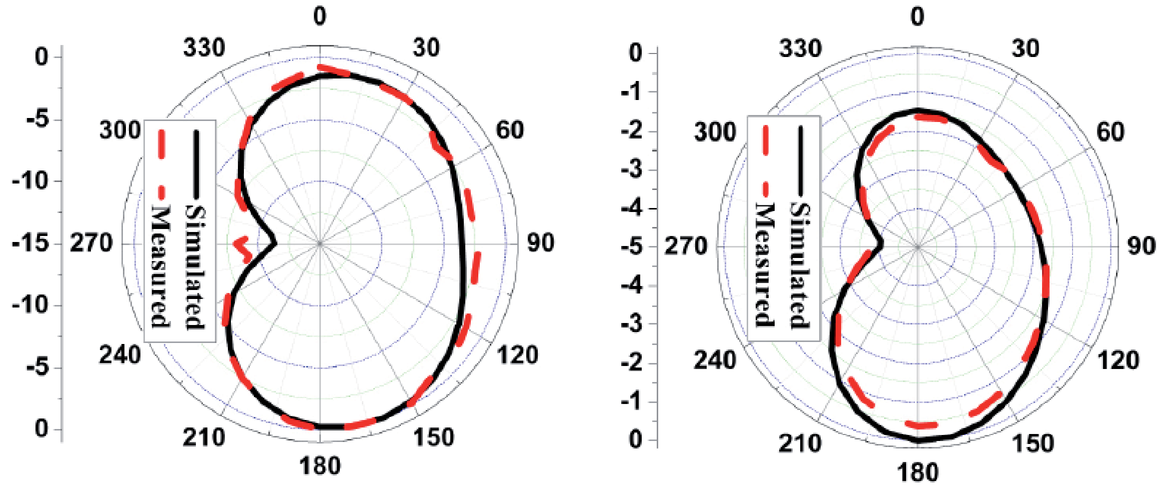

Figure 8. MIMO antenna radiation patterns at 2.08 GHz in (a) the *xz* plane and (b) the *yz* plane.

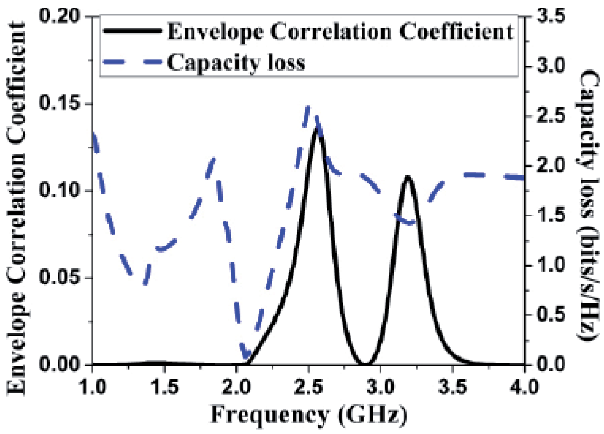

Figure 9. The measured MIMO parameters (ECC and capacity loss).

the second FSS is identified as FSS_2. The design of a single unit cell of FSS_1 is shown in Figure 10a, and a plot of its S parameters is shown in Figure 10b. FSS_1 exhibited bandpass characteristics at 10.6 GHz, with reflection coefficient (R_C) and transmission coefficient (T_C) values of around −15 dB and 0 dB, respectively. FSS_1 was arranged in the ground plane of the MIMO antenna in such a way that the upper conductive microstrip line part was backed by a PEC [7], as shown in Figure 11a. With this arrangement, not only radiating part of the antenna but also the decoupling network did not get disturbed. Reducing the RCS was hence possible without disturbing both the antenna characteristics and the isolation between the antenna elements. If a different isolation-enhancement network other than the decoupling network was used, then it would not have been easy to maintain high isolation between the antenna elements by arranging the FSS array in a ground plane. From Figures 4b and 11b, it was observed that the S parameters remained same for the MIMO antenna when backed by either a PEC or FSS_1.

Since FSS_1 acted like a transmitter of an EM wave at 10.6 GHz, an RCS reduction of more than 15 dB was achieved at the same frequency by the MIMO antenna backed by FSS_1 as compared to the MIMO antenna backed by the PEC, as shown in Figure 12b. Since FSS_1 had four-fold symmetry, it remained polarization-angle insensitive.

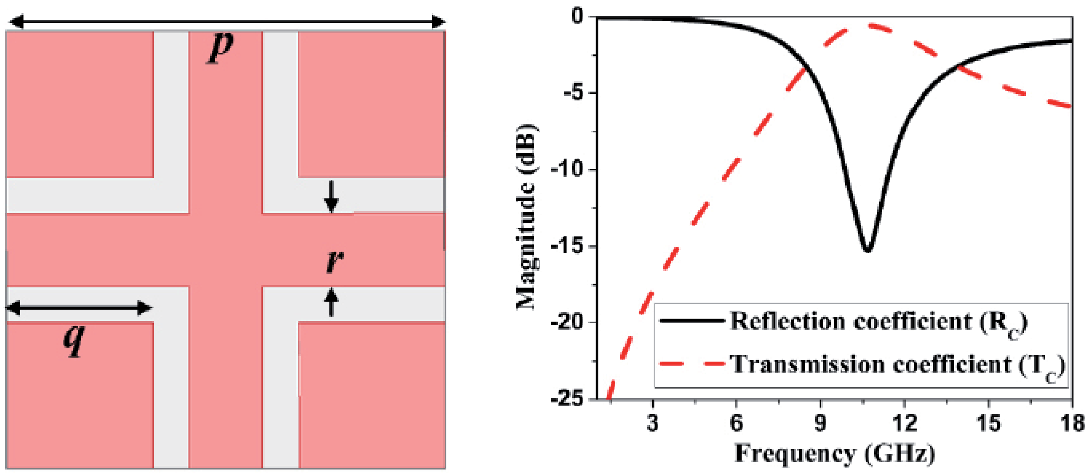

Figure 10. (a) The FSS_1 unit cell and its (b) reflection and transmission properties (simulated) ($p = 6$ mm, $q = 2$ mm, $r = 1$ mm).

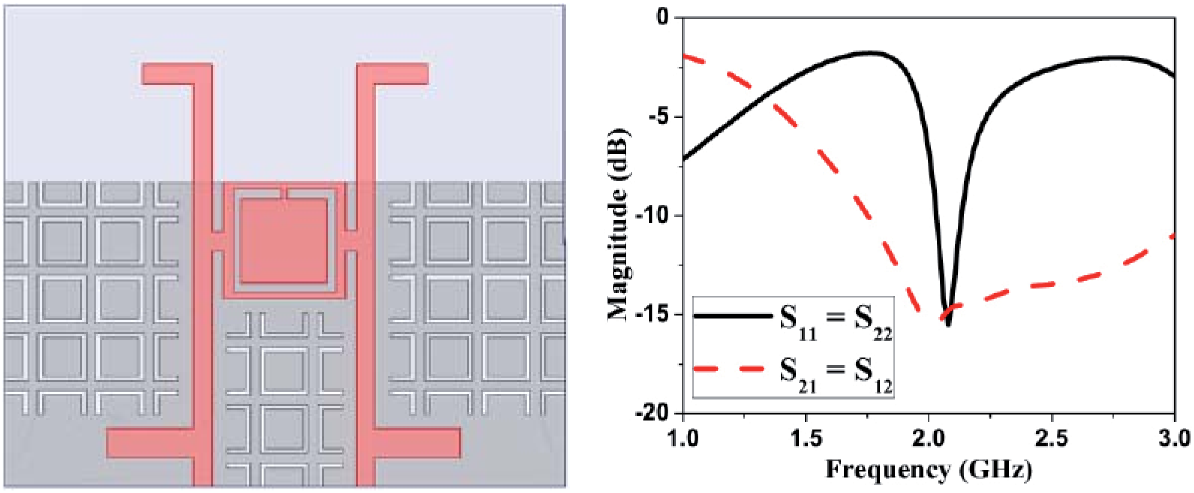

Figure 11. (a) The design of the MIMO antenna with an array based on FSS_1 as its background, and its (b) simulated *S* parameters.

However, by increasing the angle of incidence, reflections from FSS_1 drastically increased, as shown in Figure 12a. For incident angles of more than 60°, FSS_1 almost lost its bandpass property at 10.6 GHz. From Figure 12b, it could be observed that the amount of RCS reduction also drastically decreased for higher incidence angles. From Figures 12a and 12b it could thus be concluded that the reflections from FSS_1 played a prominent role in finding the RCS of the proposed design.

To understand this theoretically, an explanation using ray theory was given. The FSS reflection coefficient under normal incidence can be written as

$$\Gamma_{FSS} = \frac{\eta_{FSS} - \eta_0}{\eta_{FSS} + \eta_0}, \tag{1}$$

$$\eta_{FSS} = \eta_0 \sqrt{\frac{\mu_{FSS}}{\varepsilon_{FSS}}},$$

where μ_{FSS}, ε_{FSS}, and η_{FSS} are respectively the permeability, permittivity, and intrinsic impedance of the FSS. Γ_{FSS} is the reflection coefficient of the FSS under normal incidence. η_0 is the free-space intrinsic impedance.

When the permittivity and permeability of the FSS in Equation (1) become equal to the free-space intrinsic impedance, reflections from the FSS become very small, and a reduction in the RCS is possible for the MIMO antenna with the FSS as compared to a MIMO antenna with a PEC. However, it is not that simple to analyze the reduction in RCS when the antenna is under oblique incidence. The reflection coefficient at oblique incidence for TE polarization can be written as

$$\Gamma_{OTE} = \frac{\eta_{FSS} \cos\theta_i - \eta_0 \cos\theta_t}{\eta_{FSS} \cos\theta_i + \eta_0 \cos\theta_t}, \tag{2}$$

where Γ_0 is the oblique-incidence reflection coefficient,

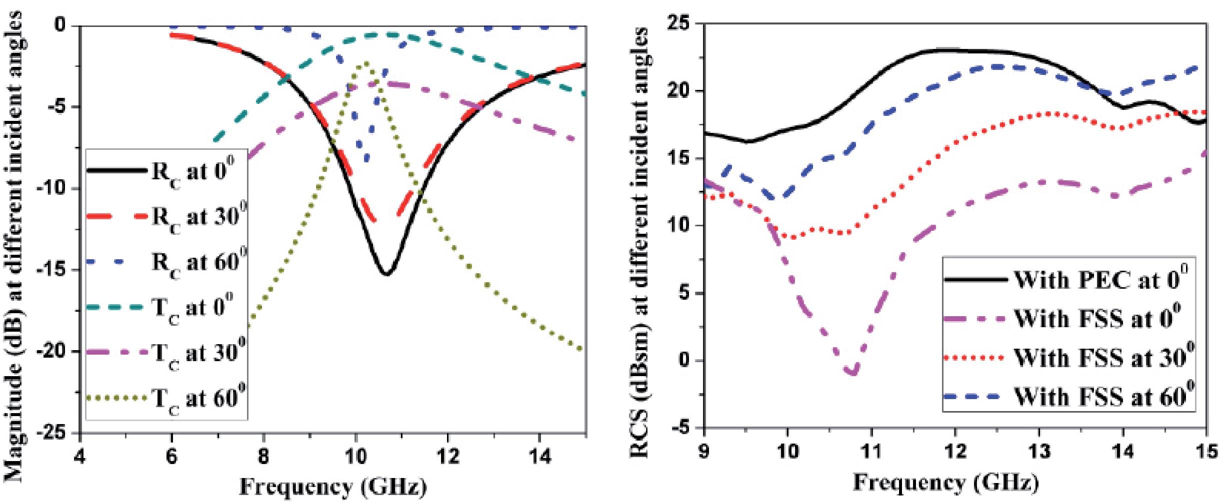

Figure 12. (a) The simulated T_C and R_C for FSS_1 at oblique incidence, and (b) the simulated RCS of the MIMO antenna with FSS_1 at oblique incidence.

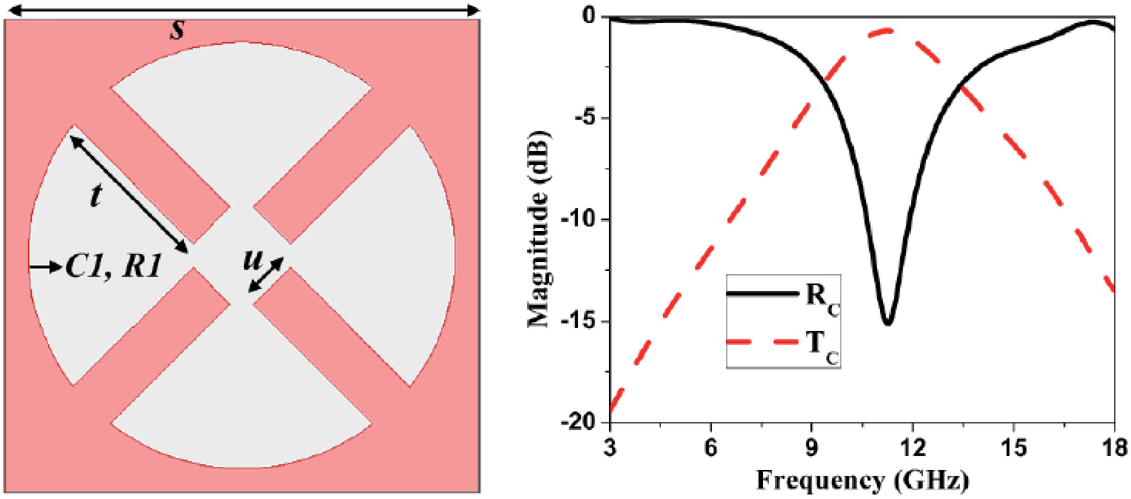

Figure 13. (a) The unit cell of FSS_2, and its (b) simulated reflection and transmission ($s = 6$ mm, $t = 2.136$ mm, $u = 0.659$ mm, $C1 = (3$ mm, 3 mm$)$, $R1 = 2.7$ mm).

and θ_i and θ_t are the angles of incidence and transmission. By using Snell's law, the relationship between the intrinsic impedance of free space and the impedance of the FSS can be written as

$$\frac{\eta_0}{\eta_{FSS}} = \frac{\sin\theta_t}{\sin\theta_i} . \tag{3}$$

By solving Equations (3) and (2), the minimum reflection condition can be obtained:

$$MR_{cri_{TE}} = \mu_{FSS}\varepsilon_{FSS} - \varepsilon_{FSS}^2 \sin^2\theta_i - \mu_{FSS}^2 \cos^2\theta_i = 0 \tag{4}$$

For the TM-polarized wave, the reflection coefficient under oblique incidence can be written as

$$\Gamma_{OTM} = \frac{\eta_{FSS}\cos\theta_t - \eta_0\cos\theta_i}{\eta_{FSS}\cos\theta_t + \eta_0\cos\theta_i} . \tag{5}$$

By following a similar procedure, the minimum-reflection condition for TM polarization was calculated:

$$MR_{cri_{TM}} = \mu_{FSS} - \varepsilon_{FSS}\sin^2\theta_i - \mu_{FSS}\varepsilon_{FSS}\cos^2\theta_i = 0 \tag{6}$$

It could be observed from Equations (4) and (6) that when the incidence angle changed, reflections from the FSS also drastically varied for both TE and TM polarizations. Since reflections from the FSS increased with an increase in incidence angle, the RCS of the MIMO antenna backed by the FSS also increased. To make the RCS of the MIMO antenna insensitive as a function of incidence angle for both the polarizations, an angularly stable FSS needed to be designed.

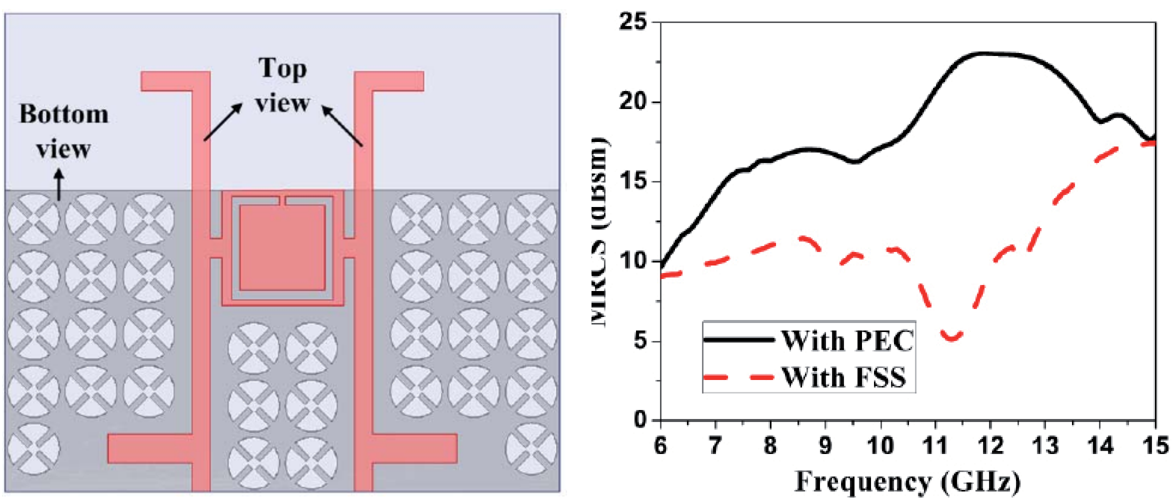

Figure 14. The final proposed low-RCS MIMO antenna: (a) design and (b) simulated monostatic RCS.

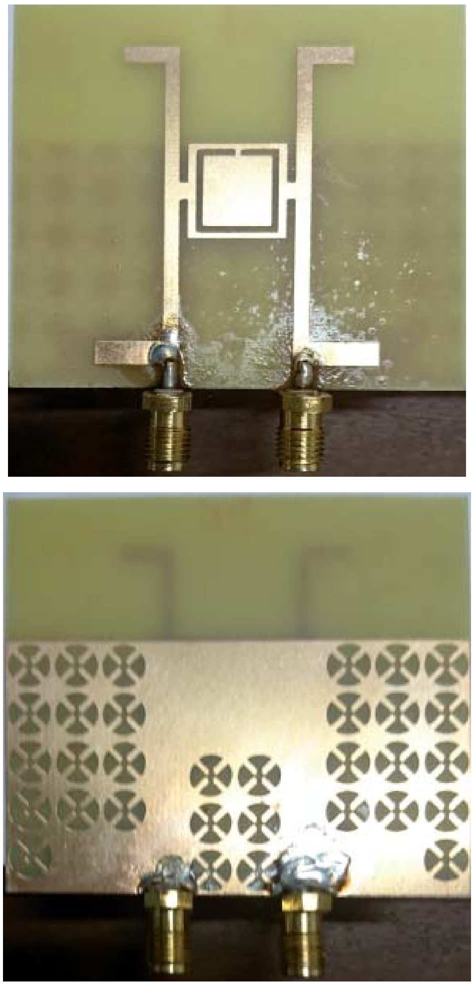

Figure 15. Fabricated (a) top and (b) bottom portions of the proposed low-RCS MIMO antenna.

In Figure 13, a polarization and incidence-angle-insensitive FSS is shown. The four-fold symmetry of the FSS contributed to polarization-angle insensitivity, and the four circular sectors present in the FSS contributed to incidence-angle insensitivity. The designed angularly stable FSS was denoted FSS_2. In Figure 14a, FSS_2 was incorporated into the ground plane of the MIMO antenna. At 11.3 GHz, FSS_2 exhibited bandpass characteristics, as shown in Figure 13b. At the same 11.3 GHz, the maximum RCS reduction was hence achieved by the proposed antenna as compared to the reference antenna, as shown in Figure 14b. With FSS_2, the reduction in RCS was achieved from 6 GHz to 15 GHz with a maximum value of more than 15 dB at 11.3 GHz. The top and bottom views of the final fabricated low-RCS MIMO antenna (i.e., the MIMO antenna with FSS_2) are shown in Figures 15a and 15b, respectively. In Figures 16a-16c, the reflection and transmission properties of FSS_2 are shown when it was under different polarizations and incidence angles. For all the polarization angles, FSS_2 provided a stable response as shown in Figure 16a. Up to incidence angles of 60°, the reflection and transmission properties of FSS_2 remained stable for both polarizations, as shown in Figures 16b and 16c.

It could also be observed from Figures 16b and 16c that the transmission and reflection properties of FSS_2 at different incidence angles were not affected by a change in polarization from TM to TE. The RCS of the MIMO antenna

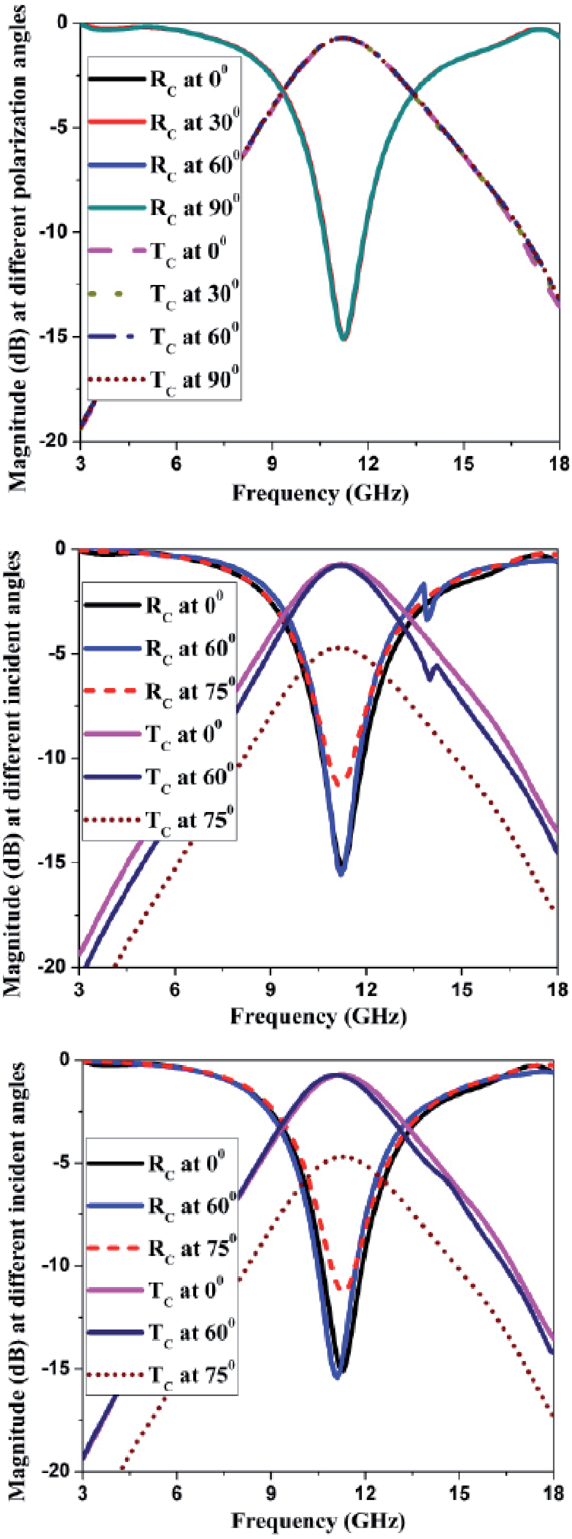

Figure 16. The simulated T_C and R_C of FSS_2 at different (a) polarization angles and (b) incidence angles for a TE plane wave, (c) and incident angles for a TM plane wave.

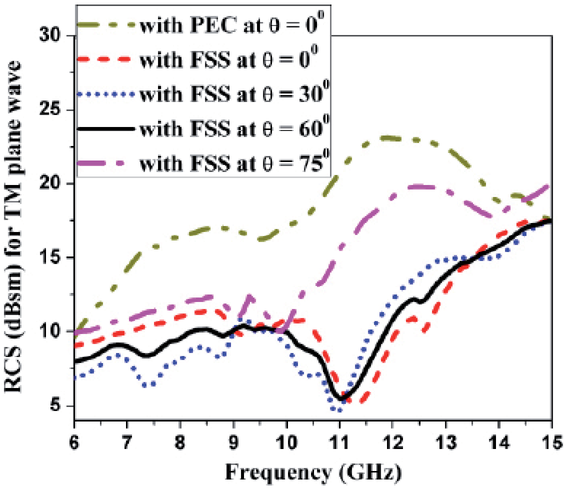

Figure 17. The RCS of the MIMO antenna with FSS_2 at various oblique incidence angles under TM polarization.

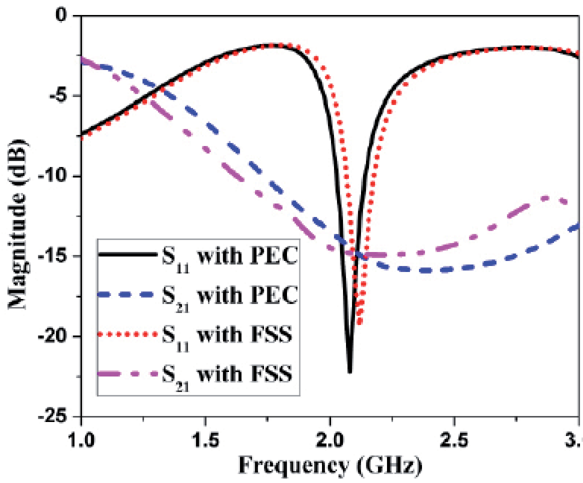

Figure 18. A comparison of measured *S* parameters of the MIMO antenna when backed by PEC and FSS_2.

with FSS_2 at various oblique incidence angles hence also remained unchanged with a change in polarization from TM to TE. Because of this, we measured the RCS of the MIMO antenna with FSS_2 only for TM polarization. The measured RCS results are shown in Figure 17. The same results were also valid for TE polarization, except for small variations that were due to the upper conductive microstrip part. Up to incidence angles of 60°, an almost constant RCS reduction was achieved by the proposed antenna as compared to the reference antenna, as shown in Figure 17. The simulated *S* parameters were validated by measuring them, as shown in Figure 18. With the proposed technique, the reduction in RCS was achieved while preserving the antenna's characteristics. This statement can be verified using Figure 19, in which the measured radiation patterns of MIMO antennas backed by both PEC and FSS_2 are shown. In both the *xz* and *yz* planes, the radiation patterns of the final low-RCS MIMO antenna perfectly matched with the MIMO antenna backed by the PEC. By just replacing the PEC with the angularly stable FSS, the proposed MIMO antenna with a filter-based decoupling network has achieved great practical usefulness.

4. Conclusion

In this paper, a technique for achieving RCS reduction for a two-port MIMO antenna has been presented. Before directly moving into the RCS reduction process, a filter-based decoupled network was designed to improve the isolation among the antenna ports in the MIMO system. Since the decoupling technique presented in this paper is a generalized technique, it can be easily applied to multi-band multi-port MIMO antennas; however, in that case, a multi-frequency band-stop filter would be required. By accommodating an FSS in the ground plane of a MIMO antenna, a reduction in RCS was achieved from 6 GHz to 15 GHz. Unlike previously published RCS reduction techniques, this paper achieved a constant RCS reduction for incidence angles of up to 60°.

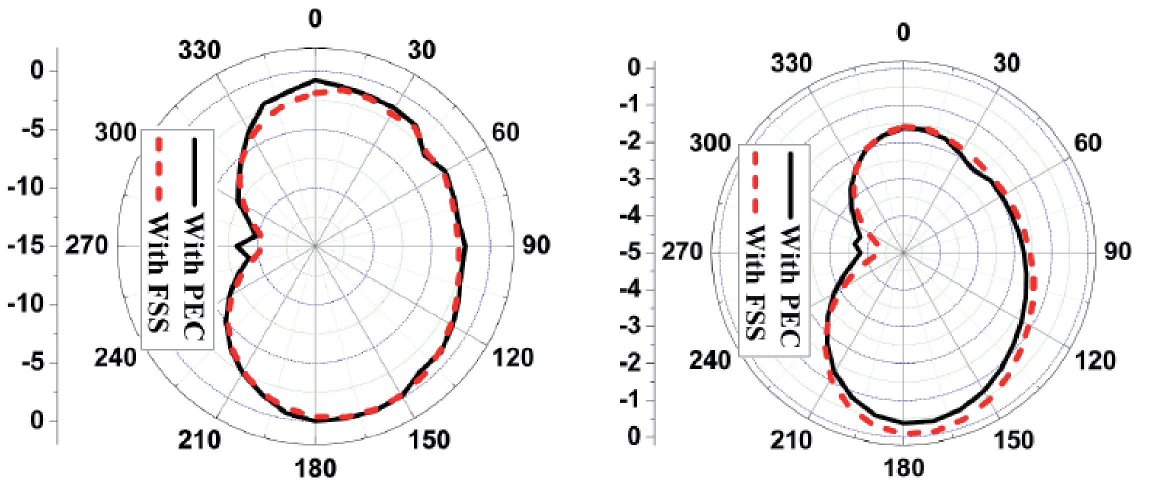

Figure 19. A comparison of the radiation patterns of the MIMO antenna when backed by PEC and FSS_2 in (a) the *xz* plane and the (b) *yz* plane (measured results).

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A Technique for Non-Contact Identification of Liquids in Closed Containers Using Microwave Planar Metamaterial

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Abstract

At present, the fast non-contact identification of liquids is a real-life task for security systems and quality testing of various drinks. The possibility of identifying liquids in containers using a technique based on two oppositely connected planar photonic crystals (PPCs) with microwaves was experimentally demonstrated. The influence of the thickness of the container's walls, the container's diameter, and the inclination angle of the container axis relative to the plane of the planar photonic crystal on the reliability of the non-contact identification of liquids was experimentally investigated. The minimum change in the concentration of aqueous solutions of ethyl alcohol, sugar, and food salt that could be reliably distinguished in solutions was defined. For liquids containing water in thin plastic containers, the optimum operating frequency band (about 2 GH to 4 GHz) of the experimental setup for their identification was found. The maximum thickness of the container wall at which the required reliability of the identification of liquids was achieved was evaluated for several selected operating frequencies. The possibility of non-contact analysis of not only aqueous solutions of ethyl and methyl alcohol, but also of their mixes, was experimentally shown. The developed technique for fast non-contact identification of liquids can be applied for food quality control, security systems, and chemical technologies.

1. Introduction

Today, there is an intensive search for techniques for the non-contact identification of liquids in non-conducting containers. Such tasks are real for security systems (for example, at airports) in order to prevent illicit liquids from getting onboard, as well as for systems that control the composition of the liquids, for example, in food-production technologies. There are several ways to solve such tasks by electromagnetic methods.

For example, the method of analyzing the reflection coefficient from the open end of a waveguide to measure the complex permittivity is known [1]. However, not only the amplitude, but also the phase of the reflection coefficient, must necessarily be measured in this method. In addition, a technique for measuring the transmission coefficient of waves passing through a dielectric waveguide with a container placed nearby [2] was developed. The disadvantage of this method was that the results were too highly sensitive to the distance from the container. The method described in [3] was based on measuring the self-resonance frequency of a solenoid with a cylindrical container placed inside it.

The method described in [4] was based on measuring the parameters of the modes of the spectrum of an open-

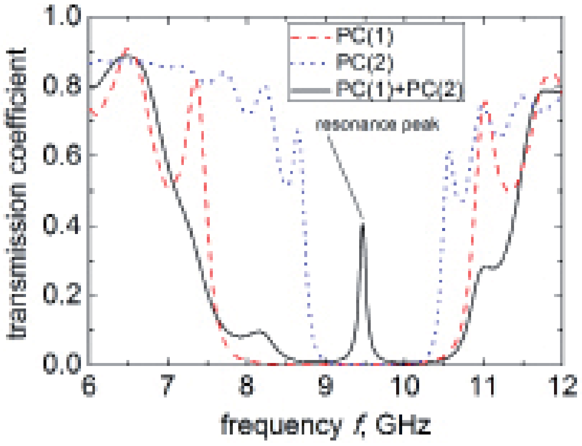


Figure 1a. The calculated spectrum of the transmission coefficient of waves passed through the different photonic crystals in a microstrip design (PPC(1) and PPC(2) curves), as well as for their serial connection (solid line).

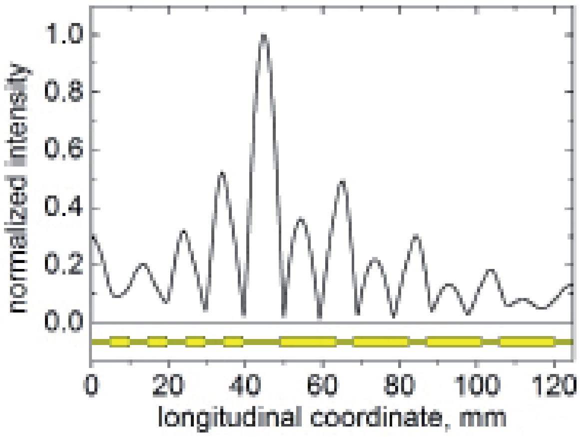


Figure 1b. The calculated distribution of the *E* field component normal to the planar photonic crystal plane along the planar photonic crystal at the frequency of the resonance peak, $f_1 = 9.5$ GHz **.**

ended waveguide with a container placed inside it. However, these methods were only suitable for analysis of containers of a fixed size. Another method was based on ultra-wideband measurement of *S* parameters of the open space with a container in the centimeter-wavelength range [5]. A similar method [6] used ground-penetrating radar for non-destructive analysis of the permittivity and conductivity of liquids in containers. The disadvantage of this technique was a very complicated method for measuring and processing the experimental data obtained.

A more promising technique used the measurement of parameters of resonator modes with a container that perturbed the resonator [7, 8]. For this technique, the principle of operation was based on the small-perturbation theory [9]. One such device using this technique has been successfully implemented in practice [8]. It used a radio-spectroscopic method, which used a combined dual-mode cylindrical resonator operating at frequencies less than 2 GHz. However, the devices based on this technique are not in widespread use because of the design complexity, the high cost, and the relatively large size. The development of a simple technique for the analysis and identification of liquids is therefore now an unsolved task.

For the technique developed by us, a structure based on a metamaterial such as the planar photonic crystal (PPC) [10, 11] was applied as an alternative to the dual-mode resonator. The suggested technique used low-cost materials and microwave components. The technique demonstrated manufacturing simplicity as well. Despite being inexpensive, the proposed method demonstrated the ability to identify liquids no worse than in [8]. Comparing the two methods presented in [8] and in the present work, we could conclude that the distinctive feature of the latter is the possibility of implementation of the final device in a more compact size.

We earlier proved the efficiency of the planar-photonic-crystal-based technique at frequencies of the order of 9.5 GHz [12-14]. At such frequencies, despite the influence of the constitutive parameters of liquids (the real and imaginary parts of the permittivity) on the microwave field in the planar photonic crystal, the parasitic effect of the container in which the liquid is placed should be taken into account [13]. By decreasing the operating frequencies to 2 GHz one could reduce the influence of the container, but this led to the unjustified increase in the size of the planar photonic crystal [14]. In addition, the influence of the diameter of the container where the liquid was placed increased. In [15], a special modification of a planar photonic crystal, which provided a reduced influence of this diameter, was proposed.

An important task is therefore to determine the influence of such container parameters as its material, diameter, and wall thickness on the reliability of non-contact identification of liquids. The aim of this paper is thus to experimentally determine the influence of structural features of planar photonic crystals and container parameters (material, diameter, wall thickness) on the reliability of the express analysis of liquids in non-conducting containers using the planar-photonic-crystal-based technique in the microwave frequency band.

2. Technique for Fast Non-Contact Identification of Liquids in the Microwave Band

As was shown in [10, 11], passing and blocking areas (pass and stop bands, Figure 1a) appear in the transmission spectrum of the planar photonic crystal (PPC) in the microstrip design. The photonic crystal is presented by alternating sections of microstrip lines of different widths.

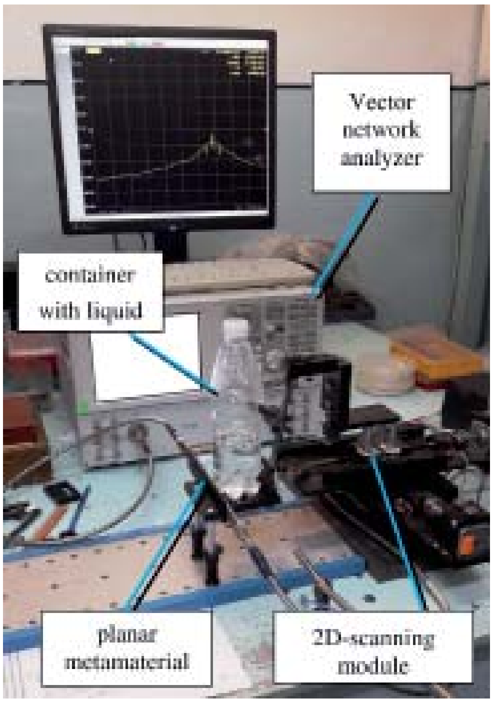


Figure 2a. A photo of the experimental setup for non-contact identification of liquids.

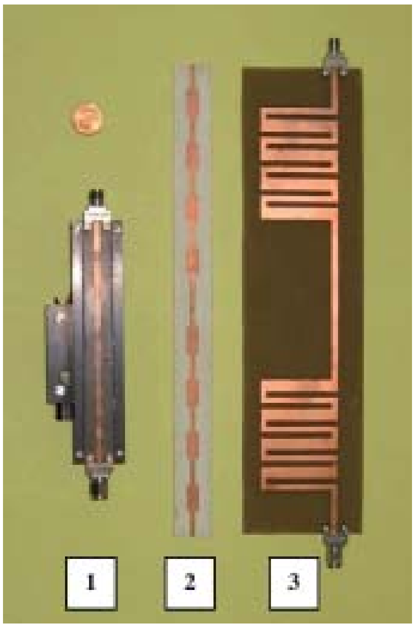


Figure 2 b. Various experimental modules based on planar photonic crystals used at the operating frequencies: $f_1 = 9.5$ GHz (1), $f_2 = 3.2$ GHz (2), and $f_3 = 1.0$ GHz (3).

Figure 1a shows the calculated transmission-coefficient spectra of waves passed through the various photonic crystals in the microstrip design. The middle of the stop band for these photonic crystals was placed near the selected frequency of $f_1 = 9.5$ GHz. When some special parameters of two different opposite connected photonic crystals were defined, a narrow transmission resonance peak appeared in the stop band (Figure 1a, the peak near the frequency of $f_1 = 9.5$ GHz). Depending on the abovementioned type of metamaterial design, this peak can be considered as an electrodynamic analog of the "Tamm" state [10] or as a defect mode/oscillation. To form a peak in the transmission spectrum, its frequency had to lie within the boundaries of stop bands for both photonic crystals, and the effective wave impedances for both contacting photonic crystals at this frequency had to be equal. In this case, a concentration of electromagnetic energy was observed [10] (Figure 1b) at the interface between the two photonic crystals. In this figure, the calculated distribution of the component of the *E*-field normal to the planar photonic crystal plane along the planar photonic crystal symmetry plane at a distance of 0.5 mm from the planar photonic crystal's surface at the frequency of the resonance peak, $f_1 = 9.5$ GHz, is shown. It is easy to see the field maximum near the interface of the two photonic crystals that is schematically shown in Figure 1b.

The experimental setup for non-contact identification of liquids using metamaterial based on planar photonic crystals in microstrip design is shown in Figure 2a [12]. It consisted of a metamaterial connected with coaxial-microstrip adapters and coaxial cables with a vector network analyzer, N5230A, which was used to measure the transmittance of electromagnetic waves in a selected frequency band. For an accurate (about 0.1 mm) positioning of the container with the measured liquid relative to the interface between the two photonic crystals, a two-coordinate scanning device was used [16].

During the experiment, certain parameters of the resonance peak were determined [12]. In particular, the measured spectrum of the transmission coefficient of the electromagnetic wave that passed through the metamaterial based on the planar photonic crystals was approximated by the Lorenz curve, using the least-squares method with fitting parameters *a*, *b*, *c* and f_{res}:

$$T = c + \frac{a}{1 + b\left(f - f_{res}\right)^2} . \qquad (1)$$

Based on the obtained approximation dependence, such parameters of the resonance peak as the resonance frequency, f_{res}, and the quality factor, $Q = f_{res}\sqrt{b\left(1+\sqrt{2}\right)}\big/2$, for the width at the level $1/\sqrt{2}$ of the maximum value, are then determined [12].

It was experimentally shown [12-14] that when a container with a liquid is placed at a small enough distance from the interface/boundary between two planar photonic crystals (the planar-photonic-crystal working area), the parameters of the resonance peak change. For a visual representation of these parameters, the graphic format was chosen in coordinates $1/Q = f\left(f_{res}\right)$ on the distance to the planar photonic crystal's interface, h_{var}, where $1/Q$ is the inverse Q factor, and f_{res} is the resonant frequency of the peak [8]. Note that according to the small-perturbations theory [8, 9], the resonant frequency is mainly affected by the real part of the permittivity, and therefore the inverse Q factor is mainly affected by the imaginary part of the permittivity. For a fixed distance h_{var} from the planar photonic crystal's interface to the container with the liquid, measured normally to the metamaterial plane, we have one point on the graph in these coordinates. By changing the distance h_{var}, we obtain a set of values for the parameters f_{res} and $1/Q$, which is conveniently represented as a curve on the graph (Figure 3). In this case, it is convenient to normalize the values of the resonance frequency and the inverse quality factor to those values that are observed when the container with the liquid is removed from the working area in the vicinity of the planar photonic crystal's interface.

The next step is to compare the measured curve for the liquid under test with the already existing set of curves for known liquids. After the comparison, the curve from the set that lies most closely to the measured curve for the unknown liquid is selected. This leads to its identification [12].

Naturally, when the values of complex permittivity of several different liquids coincide at a given operating frequency, we obtain the same curves. It is also possible that liquids with different permittivity will give similar points on the curve at different distances h_{var} from the planar photonic crystal's interface. This can happen because each liquid does not correspond to one point on the graph, but corresponds to some curve for different distances. In rare cases, this curve may intersect with the curve for another liquid. For the real liquid identification process, it is therefore recommended to measure the f_{res} and $1/Q$ at several distances, h_{var}, and not at one fixed distance. In order to increase the reliability of liquid identification, it is also possible to carry out measurements at different frequencies using the same planar-photonic-crystal-based setup, since it can have several resonant frequencies [10, 11].

3. Definition of the Optimal Parameters of the Experimental Technique for Fast Non-Contact Identification of Liquids in the Microwave Band

To define the influence of the operating frequency on the reliability of identification of a liquid in a container, the following studies were carried out. During the measurements of parameters of various liquids in the thin polystyrene container, the different characteristics of the dependence of the inverse quality factor, $1/Q$, and the resonance frequency, f_{res}, on the distance h_{var} was experimentally shown (Figure 3) [12-14]. Three different frequencies were chosen for the study: $f_1 = 9.5$ GHz (Figure 3a), $f_2 = 3.2$ GHz (Figure 3b), and $f_3 = 1.0$ GHz (Figure 3c). The metamaterials based on planar photonic crystals with these operating frequencies were designed and manufactured (Figure 2b). To reduce the size of the planar photonic crystal with the operating frequency of 1.0 GHz (Figure 2b, item 3), areas with different widths of the microstrip line were laid in meander-like style.

Note that with increasing of an electromagnetic wave absorption in liquid, the Q factor of the peak decreased with fixed h_{var}. This led to the shift of the abovementioned curve upwards. For three selected liquids, water had the greatest absorption for the operating frequencies of $f_1 = 9.5$ GHz and $f_2 = 3.2$ GHz, and therefore had the greatest value of the inverse quality factor. Ethyl alcohol had the highest absorption at the operating frequency of $f_3 = 1.0$ GHz, which was caused by its own resonant absorption frequency near 1 GHz. However, the liquids having low losses at microwave frequencies (such as vacuum oil – BM-6), have relatively small effects on the inverse Q factor of the peak. This latest fact is to expected. As can be seen from Figure 3, the working distance at which the highest reliability of liquid identification was achieved did not exceed approximately 2 mm for the frequency of $f_1 = 9.5$ GHz, and 3 mm for the frequencies of $f_2 = 3.2$ GHz and $f_3 = 1.0$ GHz. This distance is defined not only by the operating frequency, but also by the accuracy of the determination of the resonant frequency and inverse Q factor of the peak.

To define the reliability of the liquid identification using a planar-photonic-crystal-based technique at the operating frequency of $f_1 = 9.5$ GHz, a study of aqueous solutions of ethyl alcohol, salt, and sugar was carried out [12, 13]. The influence of the concentrations of ethyl alcohol (Figure 4a), food salt (Figure 4b), and sugar (Figure 4c) in a water solution in a thin polystyrene container on the form of the dependence of $1/Q$ and f_{res} on the distance, h_{var}, to the container containing the liquid was studied. In more detail, the mass concentration of salt in a saturated solution was taken as 100%. Additionally, a study of the influence of water temperature on the dependence of the peak parameters on the distance h_{var} (Figure 4d) was carried out.

From Figure 4, it could be seen that increasing the concentration of some selected additions to aqueous solutions led to the decrease of the inverse Q factor because of the reduction of the imaginary part of the solution's permittivity. All dependencies in the figures were clearly distinguishable. For example, the minimum distinguishable concentration increment of ethanol (or sugar) in solutions was about 10%, and for salt solutions it was about 20%. It could be seen from Figure 4d that a change of the water temperature of approximately 5° led to noticeable changes (which exceeded the experimental error) in the curve. This made it possible to thus estimate the temperature of water-based solutions.

To define the influence of the container's position relative to the interface of the planar photonic crystals on the reliability of the identification of liquids, the influence

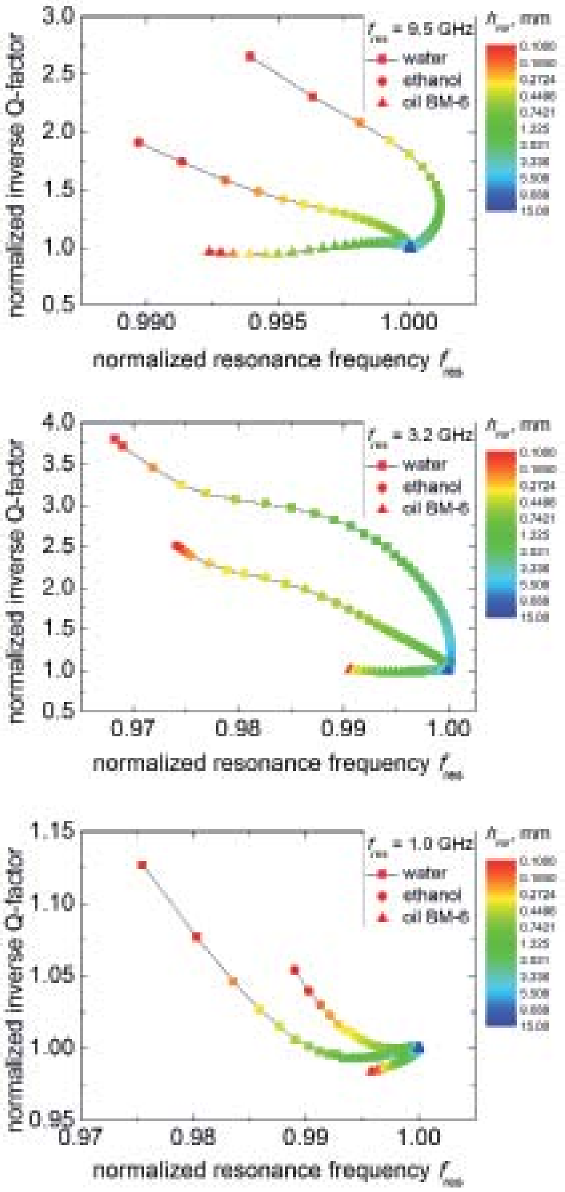


Figure 3. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the polystyrene container with different liquids for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, (b) $f_2 = 3.2$ GHz and (c) $f_3 = 1.0$ GHz.

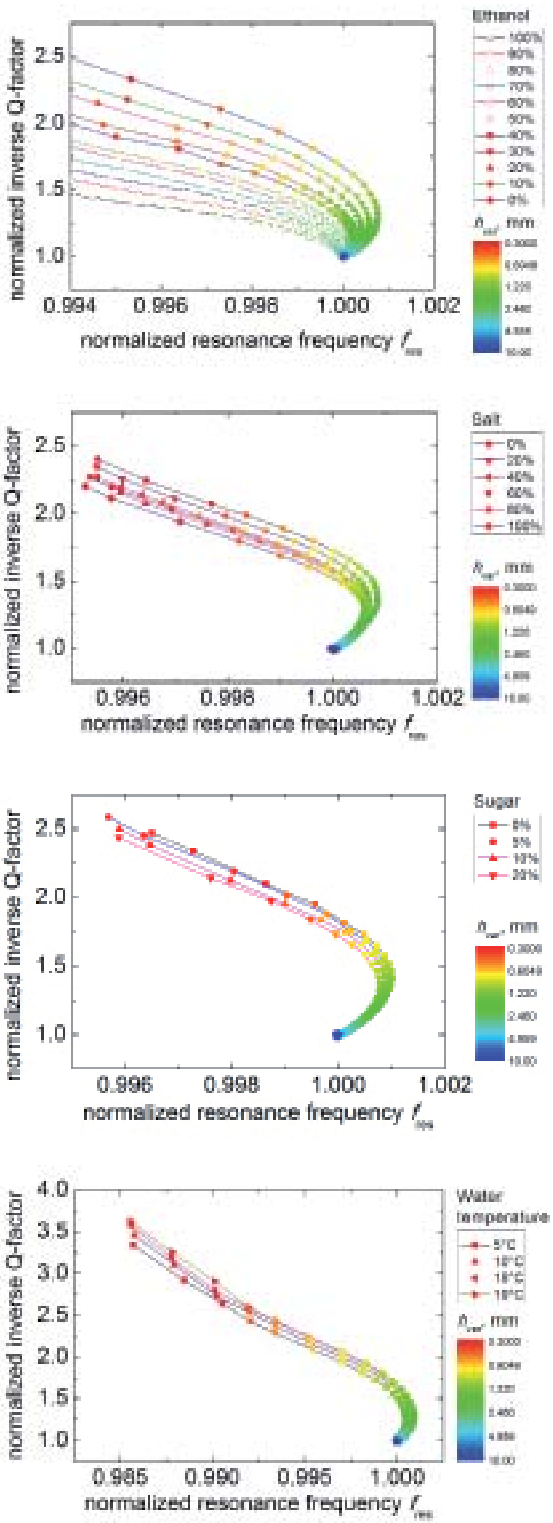


Figure 4. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the container with liquids: (a) for various concentrations of ethyl alcohol in water; (b) for various concentrations of food salt in water (relatively to the concentrated solution); (c) for various concentrations of sugar in water; (d) for different water temperatures.

of the vertical inclination angle of the container with water on the transmission peak parameters was studied. The change in the shape of the dependence of $1/Q$ and f_{res} on the distance h_{var} was analyzed for two cases (Figure 5) [13]. In the first case, the slope of the symmetry axis of the cylindrical PET (polyethylene terephthalate) container varied in the plane normal to the planar photonic crystal's plane (Figure 5a). In the second case, this axis laid in a plane parallel to the planar photonic crystal's plane (Figure 5b). In both cases, as the inclination angle of the container axis increased, the resonance frequency, f_{res}, shifted toward higher frequencies by a value of about 5×10^{-5} with a

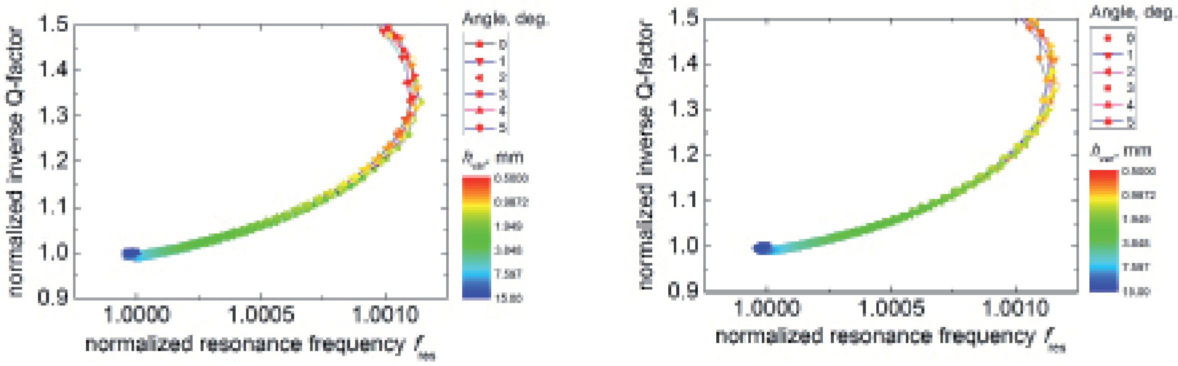


Figure 5. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the container with water and for various values of the vertical inclination angle of the axis of symmetry of the PET container in the plane: (a) normal to the plane of the planar photonic crystal; (b) parallel to the plane of the planar photonic crystal.

inclination of $1°$. At the same time, the values of frequency shift that were observed when the additions to the liquid reached the concentration of about 10% (Figures 4a-4c) or values of frequency shift that were observed with a liquid temperature variation of 5°C (Figure 4d) appeared much greater than frequency shifts caused by the slope of the container's axis.

The next stage of the work was to determine the influence of the container's wall thickness on the reliability of identification of liquids at various frequencies ($f_1 = 9.5$ GHz, $f_2 = 3.2$ GHz, and $f_3 = 1.0$ GHz) [14]. The dependencies of the values $1/Q$ and f_{res} on the distance, h_{var}, for water in cylindrical polyethylene terephthalate copolymer (coPET) containers with wall thicknesses from $h = 0.4$ **m** to $h = 1.6$ mm were experimentally measured (Figure 6).

It was easy to see (Figure 6) that as the operating frequency of the planar photonic crystals increases, the wall thickness of the container had an increasing influence on the measurement results. This could be explained by the fact that as the operating frequency of the planar photonic crystals increases, the ratio of wall thickness to wavelength increases.

In order to determine the reliability of the planar-photonic-crystal-based technique at various frequencies ($f_1 = 9.5$ GHz, $f_2 = 3.2$ GHz, and $f_3 = 1.0$ GHz), a series of measurements of mixed solutions of sugar and ethyl alcohol in water in containers made of the same material, but with different wall thicknesses, was carried out [14]. The concentration of ethyl alcohol in water was chosen to be 25% (a widespread value for alcoholic drinks). Mixed solutions (Figure 7) were studied at three operating frequencies in coPET containers with wall thicknesses of 0.4 mm and 1.6 mm. The sugar content varied in the range of 0 ml to 30 ml for 66 ml of a 25% solution of ethyl alcohol in water.

As could be seen from Figure 7, at the frequency of $f_1 = 9.5$ GHz (Figure 7a), the growth of the thickness of the container walls, h, led to a change of values $1/Q$ and f_{res} of an order of magnitude greater than the result of adding sugar to the solution. Note that at the frequency of $f_3 = 1.0$ GHz (Figure 7c), the effect of adding sugar became approximately twice as large as the effect of increasing h.

It could be seen that at the frequency of $f_1 = 9.5$ GHz, a significant negative effect of an increase in the container wall thickness on the reliability of the definite identification of the studied solutions was observed. To the contrary, at the frequency of $f_3 = 1.0$ GHz, the influence of the container wall thickness on $1/Q$ and f_{res} was minimal. However, at this frequency, the overall reliability of the method was minimal. This could be explained by the smallness of the container size (the diameter, d, was about 60 mm) in comparison with the wavelength and size of the working area of he planar photonic crystal used in the measurements.

To thus identify aqueous solutions it is reasonable to use operating frequencies in the 2 GHz to 4 GHz band [14]. In this case, the method demonstrated sufficient reliability for liquids, identifying the liquid with a sufficiently small influence of the wall thickness of the container. For the case of other operating frequencies, the following disadvantages were observed. At the operating frequency of $f_1 = 9.5$ GHz despite the higher sensitivity, the negative influence of the thickness of container walls (critically reducing the reliability of identification) was clearly observed. At the frequency of $f_3 = 1.0$ GHz, too small a reliability was demonstrated for the case of small container sizes (with a diameter of less than 60 mm).

It was experimentally obtained that for accurate and reliable identification of aqueous solutions, the maximum wall thickness of a coPET container for the case of an operating frequency of $f_1 = 9.5$ GHz should not exceed $h = 0.4$ mm, and for a frequency of $f_2 = 3.2$ GHz should not be more than $h = 1.6$ mm. For measuring liquids in containers with wall thicknesses $h > 1.6$ **m** (for example, a glass bottle), the identification of liquids is effectively carried out at frequencies $f_{res} < 3.2$ GHz. With a small

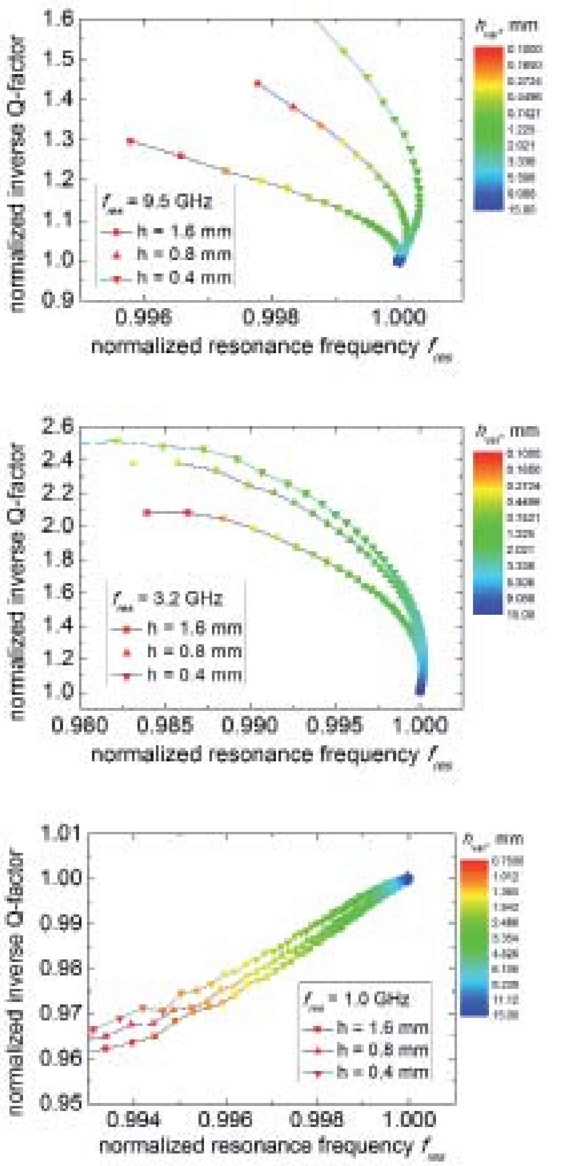


Figure 6. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the coPET container with water and various wall thicknesses, h, for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, (b) $f_2 = 3.2$ GHz, and (c) $f_3 = 1.0$ GHz.

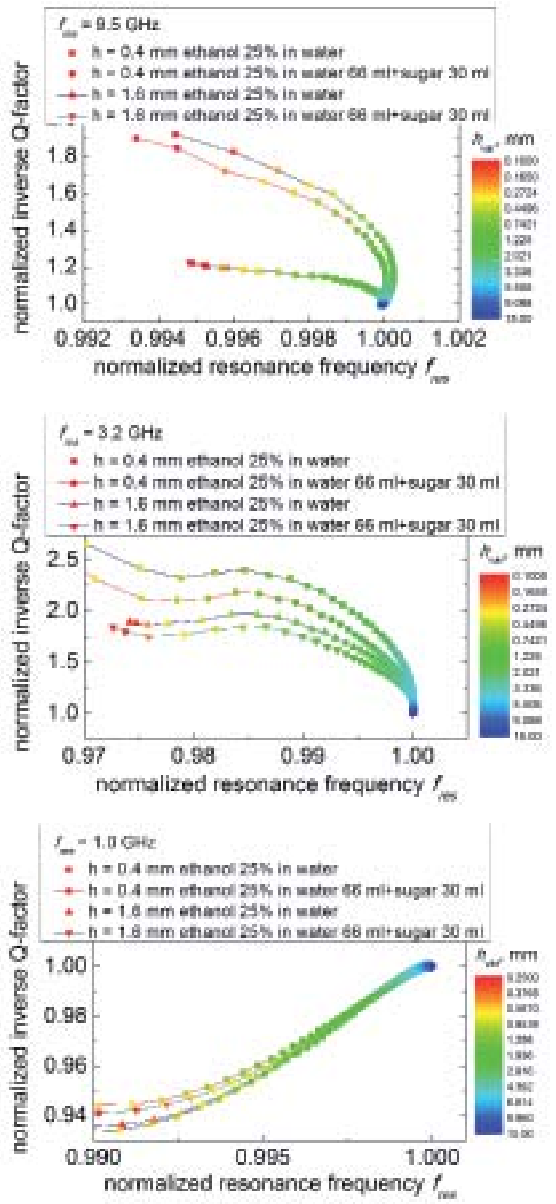


Figure 7. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the coPET container with sugar solutions in a 25% solution of ethyl alcohol in water and various wall thicknesses, h, for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, (b) $f_2 = 3.2$ GHz, and (c) $f_3 = 1.0$ GHz.

thickness of the container wall (for example, a PET bottle), the highest identification reliability is achieved at frequencies $f_{res} \geq 9.5$ GHz.

Note that the shape of the container also affects the reliability of liquid identification. A small influence of the container shape (for example, wall irregularities) was observed only for the operating frequencies of $f_2 = 3.2$ GHz and $f_3 = 1.0$ GHz, while for the frequency $f_1 = 9.5$ GHz the effect can be too large. In general, the characteristic size of the container's shape irregularities should be much less than the wavelength at the selected operating frequency.

In order to determine the effect of container diameter on the reliability of identifying liquids for the technique based on a planar photonic crystal, an additional study was carried out. A series of measurements of water in cylindrical coPET containers with wall thicknesses of $h = 0.8$ m at the operating frequency $f_4 = 2.5$ GHz, but with different diameters, *d*, of the container (Figure 8) were obtained.

As could be seen from Figure 8, an increase of the container diameter, *d*, leads to approximately the same changes in values of $1/Q$ and f_{res} as the change of the container's wall thickness at the frequency of $f_3 = 1.0$ GHz

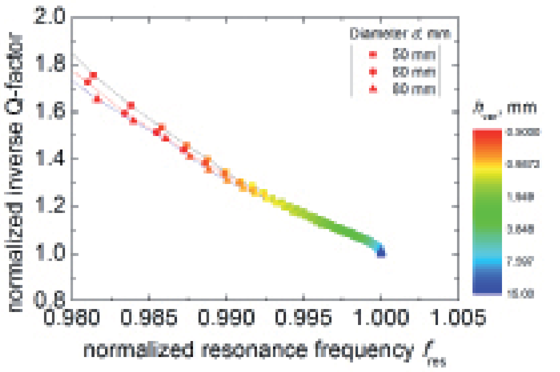


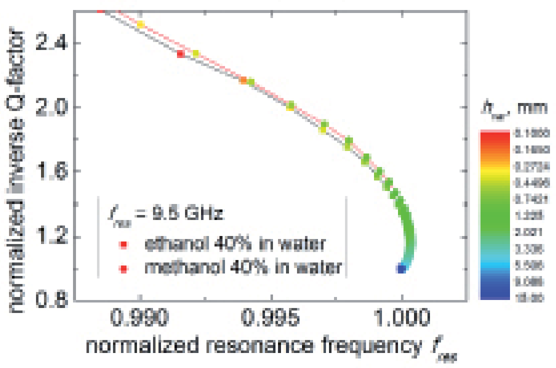
Figure 8. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the coPET container with water with different diameters of container, d, for the operating frequency of the planar photonic crystal $f_4 = 2.15$ GHz .

(Figure 7c). The diameter of the container thus has a sufficiently small influence on the reliability of identification in this case.

4. Non-Contact Identification of Aqueous Solutions of Ethyl and Methyl Alcohol Using A Technique Based on a Planar Photonic Crystal

Non-contact monitoring of the presence of hazardous methanol in alcoholic drinks is a rather real task [14]. For this purpose, the possibility of distinguishing between aqueous solutions of ethyl and methyl alcohol was investigated. The measurements were carried out in a thin polypropylene container using a metamaterial based on the planar photonic crystal (PPC). The dependencies of $1/Q$ and f_{res} on the distance, h_{var}, to the interface of the planar photonic crystals were experimentally measured at the operating frequencies of $f_2 = 3.2$ GHz and $f_1 = 9.5$ GHz (Figure 9) for three aqueous solutions: 40% ethanol (a traditional solution of strong alcoholic drinks), 20% ethanol mixtures with 20% methanol, and for 40% methanol (in this case, ethanol was completely replaced by methanol).

As could be seen from Figure 9, for the frequency $f_2 = 3.2$ GHz , a larger difference in the measured values of $1/Q$ and f_{res} for selected alcohol solutions than for the frequency $f_1 = 9.5$ GHz was obtained. This can be explained by a significant difference in the specific natural (eigen) resonant frequencies for these two alcohols. As is known, many liquids have their own resonant absorption frequencies in the microwave band. In the Cole-Cole model of permittivity, this frequency for water is about 19.7 GHz, for methanol it is about 3.2 GHz, and for ethanol is about 1.1 GHz [17]. That is, the absorption in water at the frequency of $f_1 = 9.5$ GHz significantly exceeds the absorption in alcohols. However, at the frequency of



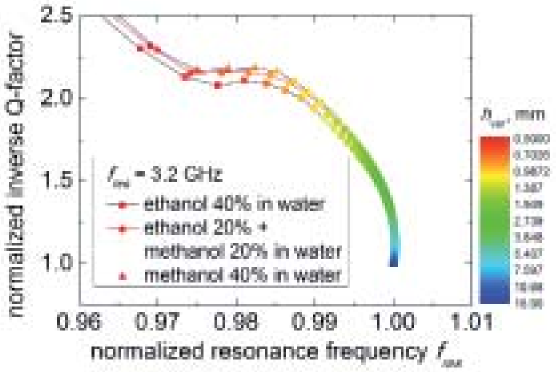


Figure 9. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res}, for different distances h_{var} from the interface of the photonic crystals to the container with ethyl and methyl alcohol solutions in water for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, and (b) $f_2 = 3.2$ GHz.

$f_2 = 3.2$ GHz , methanol makes a significant contribution to the total absorption, since its resonant frequency is close to 3.2 GHz. At the same time, the absorption in ethanol and in water is less at this frequency. This leads to a greater shift of inverse Q factor, $1/Q$, at the frequency of $f_2 = 3.2$ GHz (Figure 9b) when ethanol is replaced by methanol in aqueous solutions as compared to that observed at the frequency of $f_1 = 9.5$ GHz (Figure 9a). At the frequency of $f_2 = 3.2$ GHz it is therefore possible to distinguish not only pure alcohol solutions in water, but also their mixtures. This frequency is the best one for identification and recognition of these types of liquids among the two operating frequencies selected here.

5. The Design of a Portable Setup for Non-Contact Identification of Liquids

As a practical implementation of the above-mentioned techniques, a laboratory prototype of a portable setup for the identification of liquids was developed. In such a device, the planar photonic crystal of a special (finger-shaped) form was applied as a measuring element [15] (Figure 10). Giving such a form to the planar photonic crystal allowed us to locate the working area of the planar photonic crystal in

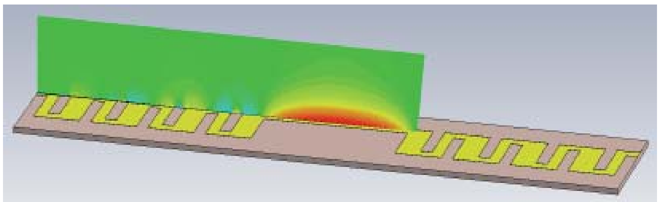
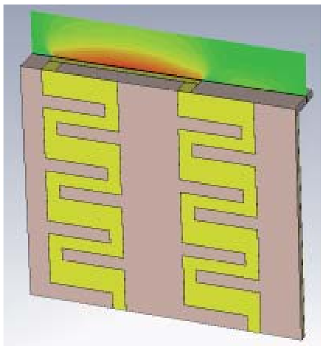


Figure 10. The spatial electromagnetic field distribution for the planar photonic crystal-based metamaterial (the normal component of the electric field): (a) "linear" planar photonic crystal and (b) "finger-shaped" planar photonic crystal.



the plane perpendicular to the plane of the rest of the planar photonic crystal, as shown in Figure 11a. This led to such a positive effect that containers (in particular, of especially large diameters) with liquids under study did not perturb the microwave field of the planar photonic crystal outside its working/resonant area (Figure 10b). This allowed us to avoid additional interaction of the microwave field with the container under study. Naturally, this positively affected the reliability of the identification of liquids.

The portable laboratory prototype (Figure 11b) for the operating frequency of $f_4 = 2.15$ GHz functionally consisted of the transceiver module, the interface and conversion module, the planar photonic crystal module, and the laptop. The overall control of the prototype device was realized by using specially designed software. At a command from the software, the oscillator in the transceiver module started to sweep the frequency in the 2.0 GHz to 2.4 GHz band. Synchronously with the process of frequency tuning, the interface and conversion module digitized the analog signal from the microwave detector located in the transceiver module. In the software window on the laptop, the spectrum of the transmission coefficient of electromagnetic waves passed throw the planar photonic crystal module was presented. Note that the system operated in real time.

By locating the container with a liquid under test in the planar photonic crystal working area (Figure 10b), we could get graphs similar to those shown in Figure 8.

The dimensions of the device shown in Figure 11 were not limited from the smallest side. In the future, the device could generally be designed as a single circuit board with the oscillator, planar photonic crystal module, microwave detector, microcontroller, interface and conversion module.

It should be noted as well that all the components of the developed prototype device used were relatively inexpensive, which was undoubtedly a positive factor for considering the question of the device's serial production.

6. Conclusions

The possibility of identifying liquids in containers using the technique based on two subsequently fitted planar photonic crystals (PPCs) in the microwave band has thus been experimentally demonstrated.

It was shown that in the process of the non-contact identification of liquids, it is necessary to take into account certain characteristics of the container in which the liquid is placed. The influence of the container on the reliability of non-contact identification of liquids using planar photonic crystals was studied. Namely, the influence of the thickness of the container's walls, the container's diameter, and the inclination angle of its axis relative to the plane of the planar photonic crystal on the parameters of the resonant transmission peak in the planar photonic crystal-spectrum were experimentally investigated.

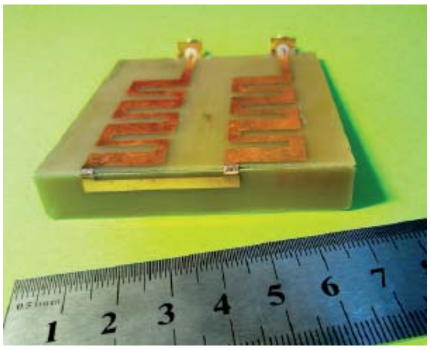
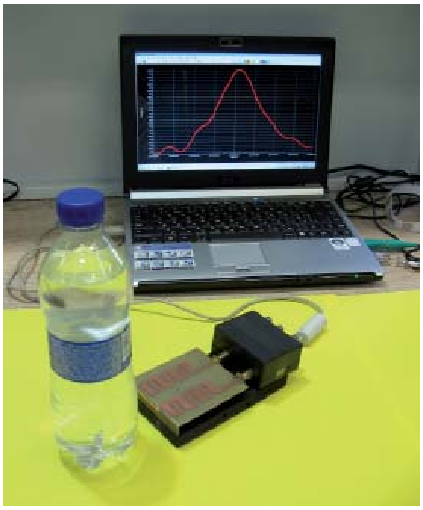


Figure 11. A photo of the (a) finger-shaped module based on planar photonic crystals; (b) portable laboratory prototype for identification and recognition of liquids in closed containers.



The minimum increment of the concentration of aqueous solutions of ethyl alcohol and sugar (10%), as well as food salt (20%), that resulted in reliable distinction of solutions was defined. For water-containing liquids in thin plastic containers, the optimal operating frequency band (of about 2 GH to 4 GHz) of the experimental setup for their identification was found. The maximum thickness of the container's wall was evaluated for several selected operating frequencies of the setup at which the required reliability of identifying liquids was achieved. It was shown that the influence of the container's wall thickness on the identification results was minimal at an operating frequency of about 1 GHz.

By using the planar-photonic-crystal-based setup, the possibility of non-contact recognition of not only aqueous solutions of ethyl and methyl alcohol, but also of their mixed solutions, was experimentally shown at microwave frequencies.

Note that the use of the principles developed and the techniques based on them for non-contact fast identification of liquids and their analysis can be applied as well to various fields of food quality-control technology, chemical technologies, etc.

7. Acknowledgment

This work was supported by NATO Science for Peace and Security Program, NATO SPS project No. 985005 (G5005).

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In Memoriam: Peter Clarricoats

Professor Peter Clarricoats, CBE, FREng, FRS, FIEEE, FIET, died on Friday, January 17, 2020, after a short illness.

Peter Clarricoats made major, fundamental contributions as a microwave engineer in the fields of applied electromagnetics for microwave and optical waveguides, and microwave antenna feeds. He was appointed a Fellow of the Royal Academy of Engineering in 1983, and was awarded the Sir Frank Whittle medal of the Royal Academy of Engineering in 2015.

He was educated at Minchenden Grammar School and Imperial College London, receiving his PhD from the University of London in 1958. He started his academic career in 1959 at Queen's University Belfast, and was subsequently appointed as a Professor at the University of Leeds in 1963, in each case starting research groups in microwave engineering that still thrive today. In 1967, he moved to Queen Mary College (now Queen Mary University of London), founding the Electromagnetics and Antenna Group, which went on to make significant contributions to antenna and microwave research.

Peter was also a pioneer of optical fibers, publishing one of the first monographs on this topic in 1975. He established the theory of electromagnetic propagation on dielectric and ferrite structures that has since been widely used in the context of optical fibers. In the course of this, he also discovered that such structures can, under some conditions, support "backward waves," and that guides can propagate complex modes.

Over the 40 years of his academic career, Prof. Clarricoats had numerous notable achievements, including pioneering designs for shaped reflectors, reconfigurable reflectors, and especially corrugated horns for microwave antennas. The latter are now universally used in satellite ground stations and in spacecraft. Peter was one of the first to recognize the radical improvements that arise from the use of a corrugated horn antenna. He went on to publish what became standard reference texts on *Corrugated Horns for Microwave Antennas, Microwave Horns and Feeds*.

His personal research was recognized through many significant awards from the IEE (now IET) and the IEEE, where he received the highest honor from the IEEE Antennas and Propagation Society (AP-S), The Distinguished Achievement Award, in 2001. His contribution to microwaves in Europe was recognized through the European Microwave Association's Microwave Prize in 1989, and the Outstanding Career Award in 2004.

Prof. Clarricoats was Vice President of the Institution of Electrical Engineers from 1989 to 1991, and Vice President and Treasurer of URSI (the International Union of Radio Science) from 1993 to 1999. He was elected Fellow of the Royal Society, the Royal Academy of Engineering, the Institute of Electrical and Electronics Engineers (IEEE), and the Institution of Engineering and Technology (IET). He was awarded with CBE in 1996.

Peter worked with other leading figures to establish new journals and conferences. Perhaps the journal he was most proud of was the internationally renowned *Electronics Letters*, which remains one of the most successful technical publications of all time.

After he retired from his full-time post in 1997, Prof. Clarricoats continued to supervise research. Through his personal innovation he developed a new compact horn design needed for satellites and spacecraft. In September 2015, he was awarded the Sir Frank Whittle medal of the Royal Academy of Engineering.

Peter had sparkle, which together with his great intellect, never left him. He will be greatly missed by the many Fellows and colleagues he mentored and encouraged throughout his career.

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In Memoriam: Iwane Kimura

Prof. Emeritus Iwane Kimura passed away on December 3, 2019. He was 86 years old. His research covered the theory and application of radiowave propagation and technology. He was a pioneer in whistler-mode ray tracing.

Prof. Kimura was Professor Emeritus of Kyoto University, and a former Dean of Information Science and Technology and Professor Emeritus of Osaka Institute of Technology. He was elected as Academician of the International Academy of Astronautics (IAA) and served as President of the Society of Geomagnetism and Earth, Planet and Space Sciences (SGEPSS). He was also an honorary member of SGEPSS, the Institute of Electronics, Information and Communication Engineers, and a Fellow of the Japan Geoscience Union. He received the Order of the Sacred Treasure, Gold Rays with Neck Ribbon (the Zuiho Middle Ribbon) in 2012 for his distinguished achievements in research.

In 1993, Prof. Kimura chaired the organizing committee of the URSI General Assembly in Kyoto, Japan. Two of his most successful students (Hiroshi Matsumoto and Yoshiharu Omura) later went on to become President and recipient of the Booker Gold Medal, and recipient of the URSI Appleton Prize.

Prof. Kimura started his scientific career in the 1950s by calculating the ray paths of whistlers in the magnetosphere. His work was inspired by the paper on whistling atmospherics by L. R. O. Storey, and he used a (Tiger) mechanical calculator to carry out the calculations. In 1964, he was invited to Stanford University, where he used Yabroff's computer ray-tracing program to study the effects of positive ions on wave propagation. He included protons, alpha particles, and oxygen ions, which were the main ionic constituents in the plasmasphere and upper ionosphere. Until then, ray tracing of whistlers had only taken electrons into account. He showed that whistler waves could be reflected at the lower hybrid resonance condition, which was a major new result.

Prof. Kimura went on to develop three-dimensional ray tracing using the IGRF magnetic field model, and to include the effects of plasma temperature. He led studies to explain the propagation and confinement of electrostatic electron cyclotron harmonic waves and Z-mode electromagnetic waves in the magnetosphere. He also performed ray tracing of ground-based VLF (OMEGA) transmitter signals observed by the Japanese Akebono (EXOS-D) satellite. He determined the global electron-density profile by comparing the wave-normal direction and the delay time obtained by the Akebono observations with those calculated by ray tracing.

Right from the beginning, Prof. Kimura was involved in a number of rocket and satellite experiments in Japan. He obtained the electron-density profile in the ionosphere through the Doppler shift of VLF waves, which depends on the ambient electron density. He used both up- and down-shifted waves, since the signs of the Doppler shift are opposite because of the spin motion of a rocket. He was Principal Investigator of the VLF instrument on the scientific satellite EXOS-B (Jikiken), which was launched in 1978 as a part of the International Magnetosphere Research (IMS).

He was one of the first in Japan to lead joint international research, which was still very unusual at that time, and went on to be Project Scientist of the GEOTAIL satellite. His group succeeded in receiving VLF radio wave transmissions in orbit from the transmitter at Siple Station in Antarctica, operated by Stanford University. This led to valuable results regarding the study of wave-particle interactions during wave propagation in space. Through these efforts, we have been able to contribute to the development of human resources and the development of Japanese space science. Prof. Kimura also greatly contributed to the development and the completion of the MU (Middle and Upper atmosphere) radar installed in Shiga, Japan.

Prof. Kimura followed the quote, "Never leave till tomorrow that which you can do today." He was famous for his quick response and highly praised as the most serious and sincere research supervisor. He showed outstanding work ability in organizing international conferences and other various things. His ray-tracing *FORTRAN* program is available at Kanazawa University (http://waves.is.t.kanazawa-u.ac.jp/), and its *MATLAB* version is available as "Ray tracing program: Investigation of WAves Near the Earth (IWANE)" at Kyoto University (http://space.rish.kyoto-u.ac.jp/software/).

We convey our greatest sympathy to his wife, Mieko, and his children and grandchildren.

Emeritus Prof. Kozo Hashimoto
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In Memoriam:
Alan S. Rodger

It is with great sadness that we report that Prof. Alan Rodger, Editor of the *Journal of Geophysical Research (Space Physics)* and former Interim Director of the British Antarctic Survey (BAS), passed away on January 3, 2020.

Alan was born in 1951, and brought up in Edinburgh, Scotland. After completing his degree in Electrical Engineering at the University of Manchester, he joined the BAS (British Antarctic Survey) in 1972 and completed two winters at the Argentine Islands station (now the Ukranian Antarctic Research Station Vernadsky). He acquired the nickname "Florence," because of his care and skill in nursing one of his companions who had suffered a serious injury in the middle of winter. His compassion and care for others marked him out as someone special.

On returning to BAS he built an international reputation, publishing over 91 research papers and widely collaborating. Alan worked on a number of problems in magnetosphere-ionosphere physics, combining ground-based observations at Halley with satellite data such as DE-2. He became well known for his work on the mid-latitude ionospheric trough. His review paper became one of his most highly cited papers. When the first SuperDARN radar was installed at Halley (originally called PACE), he was quick to exploit it. He used radars to study the ionospheric footprint of the cusp, and put forward a theory for the formation of polar patches: pointing out that a large dawn-dusk component of the interplanetary magnetic field plays a key part in their formation. His research was recognized by a DSc from the University of Manchester, and a visiting professorship at Aberystwyth University.

Alan broadened his research into climate change, and became Head of Science Programmes and then Interim Director of BAS during a difficult period. He provided the leadership and direction that was needed. He served on international committees, particularly the Science Advisory Board of the Birkland Centre for Space Science in Norway.

In retirement, Alan was a dedicated Editor of *JGR Space Physics* for six years, shepherding over 1300 manuscripts through the editorial process, and providing insightful contributions to publication policy and practice.

Alan also served on the Boards of Governors for various schools, and contributed to local Council work. He was a modest, quiet, and gentle man who always had time for others and a passion for cricket and golf. He dealt with his debilitating illness with dignity and calmness, never letting it get the better of him. He leaves behind his wife Mary, sons Chris and Alex, and a grandchild. He will be sadly missed.

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[The above item was taken in part from the American Geophysical Union *SPA Section Newsletter*, Vol. XXVII, 5, January 16, 2020.]

In Memoriam: Valerian Ilich Tatarskii

Valerian Ilich Tatarskii, a world-renowned physicist, passed away at his home in Boulder, Colorado, on April 19, 2020, at the age of 90. Prof. Tatarskii was recognized worldwide as a founder of a new field in physics, wave propagation in random media, which involves the propagation and scattering of electromagnetic and acoustic waves in a turbulent atmosphere and a fluctuating ocean.

Valerian Tatarskii was born on October 13, 1929, in Kharkov, USSR. In 1952, he received his MS from the Physics Department of Moscow State University. The subject of his thesis was sound propagation in a turbulent atmosphere. This study later progressed into his main research area: studies of electromagnetic (radio frequency and optical) wave propagation in random media. In 1953, Tatarskii joined the Laboratory for Turbulence Research at the Geophysical Institute of the USSR Academy of Sciences, which later became the Obukhov Institute of Atmospheric Physics.

Tatarskii earned his PhD in 1957. The PhD thesis was then converted into a book, *Wave Propagation in a Turbulent Medium* (1959, in Russian). Due to the importance of the topic for a variety of applications, the book was translated into English (1961 and 1967), and became an authoritative and widely referenced work. In 1964, Tatarskii received a Doctor of Science (DSc), which is similar to the Habilitation in Europe. His DSc thesis became the basis for another book, *The Effect of the Turbulent Atmosphere on Wave Propagation* (1965, in Russian), which was translated into English (1971). These two books – and a later four-volume series, *Principles of Statistical Radiophysics*, coauthored with S. Rytov and Yu. Kravtsov – became the foundations of a new field, wave propagation in random media, and established Tatarskii as a founder of this field. Dr. A. Wheelon, a respected scientist who also worked in this field, wrote in his books: "These volumes are dedicated to Valerian Tatarskii who taught us all."

Tatarskii was a Laboratory Chief at the Institute of Atmospheric Physics (1978-1990) and a Division Chief at the Lebedev Physical Institute, the USSR Academy of Sciences (1990). In 1990, after an invitation by Dr. S. Clifford, who was then Director of the NOAA Wave Propagation Laboratory (WPL), Tatarskii started to work at NOAA/WPL in Boulder, Colorado. Since 2006, Tatarskii worked at Radio-Hydro-Physics, LLC.

Tatarskii was a member of the editorial board of the Russian journal *Uspekhi Fizicheskikh Nauk* (*Advances in Physical Sciences*), an Associate Editor of the journal *Waves in Random Media* (1991-1998), a member of the editorial board of the *Journal of Electromagnetic Waves and Applications*, and a consultant for the *Great Russian Encyclopedia*.

Prof. Tatarskii was elected a Corresponding Member of the USSR/Russian Academy of Sciences in 1976, and was a recipient of the USSR State Prize (1990). In the US, he became a Fellow of the Optical Society of America, a Member of the US National Academy of Engineering (1994), and received the Max Born Award of the Optical Society of America (1994).

In his private life, Valerian Tatarskii was an avid lover of classical music: he regularly attended performances of the symphony orchestra. In winter, he enjoyed cross-country skiing in the Rocky Mountains. During the summer, he went on hiking and kayaking trips with his family and friends. He is survived by his wife, Maya; son, Viatcheslav; and two grandchildren. Prof. Tatarskii will be truly missed. His passing closes an important chapter in wave propagation in random media, the field that he largely created.

In Memoriam: Roberto Sorrentino

Professor Roberto Sorrentino, University of Perugia, Italy, an outstanding researcher in the area of microwave techniques for circuits and devices, passed away on March 3, 2020 at the age of 72.

Figure 1. Prof. Roberto Sorrentino.

Roberto Sorrentino (Figure 1) was born in Rome, Italy. He received the Laurea in Electronics Engineering from "La Sapienza" University of Rome. At the same university, he became an Assistant Professor of Microwaves in 1974, and an Associate Professor of Microwave Measurements and of Solid State Electronics in 1982. In 1983 and 1986, he was appointed a Research Fellow at the University of Texas at Austin, Austin, USA. From these visits, he started a lifelong and fruitful scientific collaboration with Prof. Tatsuo Itoh. In 1986, he was appointed Full Professor at the University of Rome "Tor Vergata." Finally, in 1990, he moved to the University of Perugia, Perugia, Italy, where he was later the Chair of the Electronics Department, Director of the Computer Centre, and Dean of the School of Engineering.

Prof. Sorrentino's research interests were focused on many hot technical subjects in the areas of microwaves and antennas. His broad knowledge allowed him to provide significant contributions to topics as different as propagation in anisotropic media and interaction of electromagnetic fields with biological tissues. However, his most outstanding contributions were in the development of effective numerical methods and CAD techniques for the analysis and design of passive microwave structures and of microwave and millimeter-wave circuits. By employing the resonant-mode expansion technique, he contributed to advances in the Planar Circuit Approach, a useful numerical tool for modeling discontinuities in planar circuits, also widely used in this era for numerical simulators. He also developed advanced mode-matching methods, and specifically contributed to the Transverse Resonance Approach for analyzing discontinuities in waveguide and planar components.

Roberto was very active in scientific associations, both nationally and internationally. He was one of the founders of the European Microwave Association (EuMA), which was created in 1998 to manage the annually held European Microwave Conference and to start the new European Microwave Week. Indeed, since 1973, he was deeply involved in the organization of the European Microwave Conference, as a member of both the Technical Program Committee and the Management Committee. He served as the first President of the Association from 1998 to 2009. In 2010, EuMA presented him its Distinguished Service Award. In 2014, he was the General Chair of the 17th European Microwave Week, which was held in Rome.

Roberto also strongly contributed to the activities of the Institute of Electrical and Electronic Engineers (IEEE), and in particular to those of the Microwave Theory and Techniques Society (MTT-S). In recognition of his achievements, in 1990 he was elected IEEE Fellow "for contribution to the modelling of planar and quasi-planar microwave and millimeter-wave circuits." In 1993, he received the IEEE MTT-S Meritorious Service Award. In 2000, he was one of the recipients of the IEEE Third Millennium Medal. In 2004 he received the Distinguished Educator Award from the IEEE Microwave Theory and Technique Society (MTT-S). In 2012, he was the recipient of the IEEE MTT-S Microwave Prize (with S. Bastioli and C. Tomassoni) for the paper, "A New Class of Waveguide Dual-Mode Filters Using TM and Nonresonating Modes" (*IEEE Trans. on Microwave Theory and Techniques*, **58**, 12, December 2010, pp. 3909-3917). In 2015, he received from the *IEEE MTT-S* the prestigious Microwave Career Award.

He was also very active in the International Union of Radio Science (URSI), serving as the Vice Chair and then Chair of URSI Commission D, "Electronics and Photonics." Since 2007, he served as the President of the Italian National Committee of URSI, playing a fundamental role in bringing the URSI General Assembly and Scientific Symposium (URSI GASS) 2020 to Rome.

In 2002, he was among the founders of the Italian Electromagnetic Society (Società Italiana di Elettromagnetismo – SIEm). In particular, he served as the first President of SIEm from 2002 to 2008.

In January 2020, Roberto was awarded the prestigious honor of the Grand Officer of the Order of Merit of the Italian Republic for his commitment to research. The award was conferred by the Head of State, Sergio Mattarella, on the proposal of the Prime Minister, Giuseppe Conte.

In September 2007, he successfully founded RF Microtech s.r.l., a spin-off company of the University

Figure 2. Prof. Sorrentino together with some of his young collaborators at RF Microtech s.r.l., Perugia, Italy.

of Perugia that specialized in RF MEMS, microwave components, systems, and antennas. The company is presently independent and employs 25 people, most of them former PhD students of the University of Perugia. In recent years, he was very active in the company, and proud of his young collaborators (see Figure 2), most of whom he used to mentor.

Roberto has inspired generations of students. He was a natural leader, always willing to help and support everyone in his group, building deep personal friendships with his close collaborators and students. He is survived by his wife, Linda.

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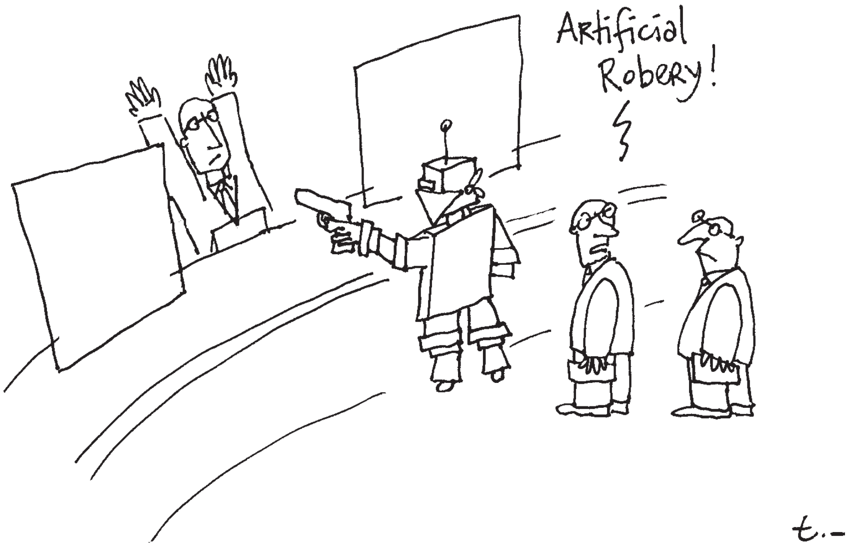

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SOLBOX-18: Near-Field Scattering from Electromagnetically Large Boxes

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1. Introduction

High-frequency techniques [1] are excellent tools for analyzing electrically large structures, especially if their geometries do not possess complex interactions, e.g., those caused by resonances. However, as the technology (both in terms of software and hardware) develops, it becomes possible to solve increasingly large problems via full-wave solvers without resorting to approximations and assumptions. Specifically, full-wave methods enable the analysis of electrically large objects with more direct applications of Maxwell's equations, while fundamental mechanisms, such as diffractions, reflections, and ray-like behaviors, are expected to be revealed as simulation results rather than being introduced as initial assumptions. Such full-wave solvers not only supply reliable simulations for arbitrarily complex structures, but also support high-frequency techniques by providing reference results for further analyses.

In this issue of Solution Box (SOLBOX-18), scattering problems involving a quite basic geometry are considered. Specifically, a metallic rectangular box is excited via plane waves at different frequencies, and it is sought to obtain near-zone electric/magnetic-field distributions at and around the box. As the frequency increases, the maximum dimension of the box reaches 64λ, where λ is the wavelength, leading to challenging simulations using a full-wave solver. By investigating the near-field results, it is particularly desired to understand the electromagnetic characteristics of the box, e.g., reflections, shadowing, diffractions, etc., at different frequencies. Interested readers are welcome to send their alternative solutions to the problems described both in this issue and in the previous issues.

2. Problem SOLBOX-18

In SOLBOX-18, we considered a 300 mm × 300 mm × 37.5 mm rectangular box, which could be assumed to be a perfect electric conductor. The box was considered to be located in vacuum, and it was excited by linearly polarized plane waves at 8 GHz, 16 GHz, 32 GHz, and 64 GHz. At these frequencies, the maximum dimension of the box corresponded to approximately 8λ, 16λ, 32λ, and 64λ.

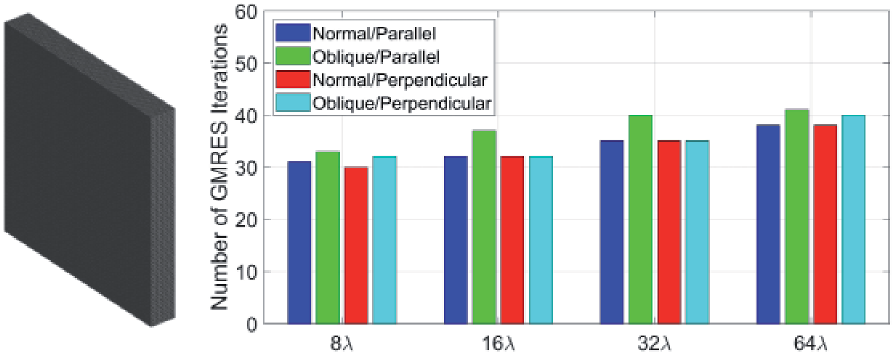

Figure 1. The numbers of GMRES iterations to solve the problems of SOLBOX-18.

Both normal and oblique incidences were considered, while the polarization could be perpendicular or parallel. The aim was to obtain the electric-field intensity, magnetic-field intensity, and/or power density at multiple locations nearby the box to investigate its electromagnetic characteristics at different frequencies.

3. Solution to Problem SOLBOX-18

3.1 Solution Summary

Solver type (e.g., Noncommercial, commercial): Noncommercial research-based code developed at CEMMETU, Ankara, Turkey

Solution core algorithm or method: Frequency-domain MLFMA

Programming language or environment (if applicable): *MATLAB +MEX*

Computer properties and resources used: 2.5 GHz Intel Xeon E5-2680v3 processors (using 1 core)

Total time required to produce the results shown (categories: < 1 sec, < 10 sec, < 1 min, < 10 min, < 1 hour, < 10 hours, < 1 day, < 10 days, > 10 days): < 30 hours for the largest problem

3.2 Short Description of the Numerical Solutions

The problems listed in SOLBOX-18 were solved in the frequency domain by using a conventional implementation of the Multilevel Fast Multipole Algorithm (MLFMA) [2]. At each frequency, the box was discretized by using small triangles ($\lambda/10$), while the Rao-Wilton-Glisson functions were employed to expand the electric-current density and to test the boundary conditions. The combined-field integral equation with equal contributions of the electric-field integral equation and the magnetic-field integral equation were used to formulate the problems. The numbers of unknowns in the constructed matrix equations were 48,000, 192,000, 768,000, and 3,072,000, respectively, at 8 GHz, 16 GHz, 32 GHz, and 64 GHz. For these sizes, the application of the recursive clustering in MLFMA led to tree structures with six, seven, eight, and nine levels. Far-zone interactions were diagonalized via plane waves, while Lagrange interpolation/anterpolation operations were used between levels. For the results presented below, far-zone interactions were computed with two digits of accuracy. Near-zone interactions were also calculated with a maximum 1% relative error using singularity extraction techniques and Gaussian quadratures. Iterative solutions were carried out by using the generalized minimal residual

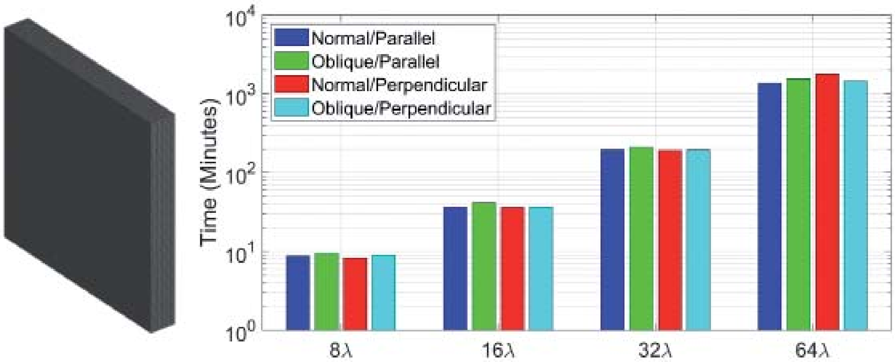

Figure 2. The processing times required to solve the problems of SOLBOX-18.

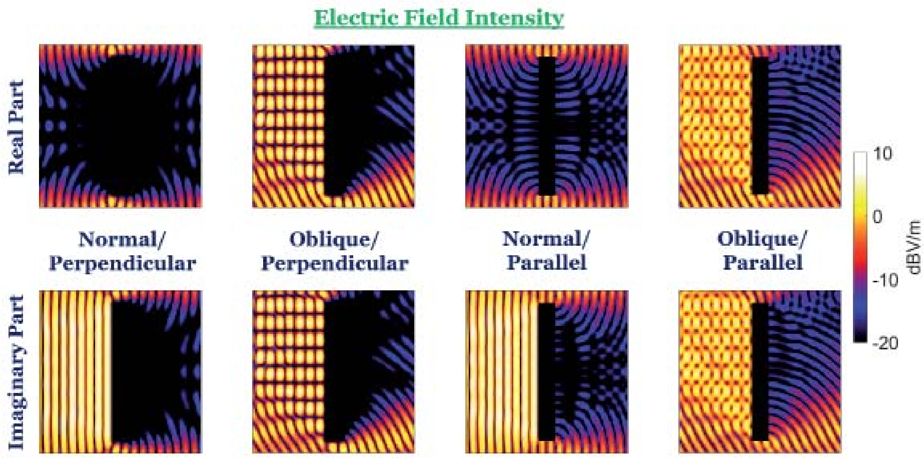

Figure 3. The electric-field intensity distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by various plane waves at 8 GHz.

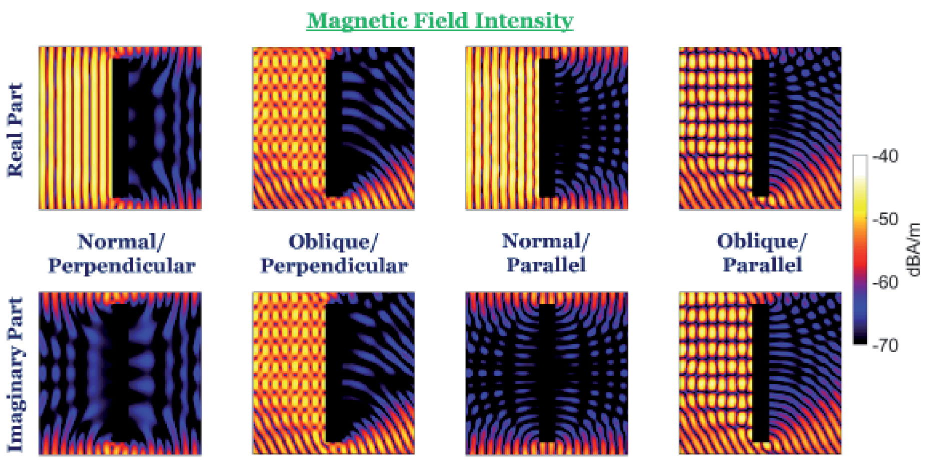

Figure 4. The magnetic-field intensity distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by various plane waves at 8 GHz.

(GMRES) method without restart and preconditioning. The target residual error for an iterative convergence was set to 0.001. Once the expansion coefficients were found, field-intensity and power-density distributions were obtained in the near zone (400 × 400 samples) via radiation integrals.

At each frequency, the box was excited by four different plane waves, i.e., normal and oblique (30°) incidences with parallel and perpendicular polarizations of the electric field. Figures 1 and 2 present the iteration counts and the processing times, respectively, required for all simulations. We observed that even without preconditioning, the solutions required only 30 to 41 GMRES iterations. For the smallest electrical size (8λ maximum dimension), the processing times were all below 10 minutes, while it took almost 30 hours to solve the normal/perpendicular excitation case for the largest electrical size. We noted that this corresponded to only a 180-fold increase, while the problem size (the number of unknowns) grew by 64 times.

3.3 Results

Figures 3 and 4 present the electric-field intensity and the magnetic-field intensity, respectively, obtained at 8 GHz. For four different excitations, the real and imaginary parts of the field distributions are separately shown. In these (and also in the following) plots, the rectangular box was located at the middle, and the fields were investigated on the plane of incidence. The waves traveled from left to right: hence, the left-hand side of a plot corresponds to the reflection region, while the right-hand side corresponds to the transmission. Figure 3 showed that for the normal-incidence cases, standing-wave behaviors dominated (in the reflection region), with strong oscillatory functions only in the imaginary parts. For the oblique-incidence cases, both real and imaginary parts were significant, while the patterns in the vertical direction demonstrated 90° phase differences, indicating traveling waves in this direction. Matching phases (between real and imaginary plots) in

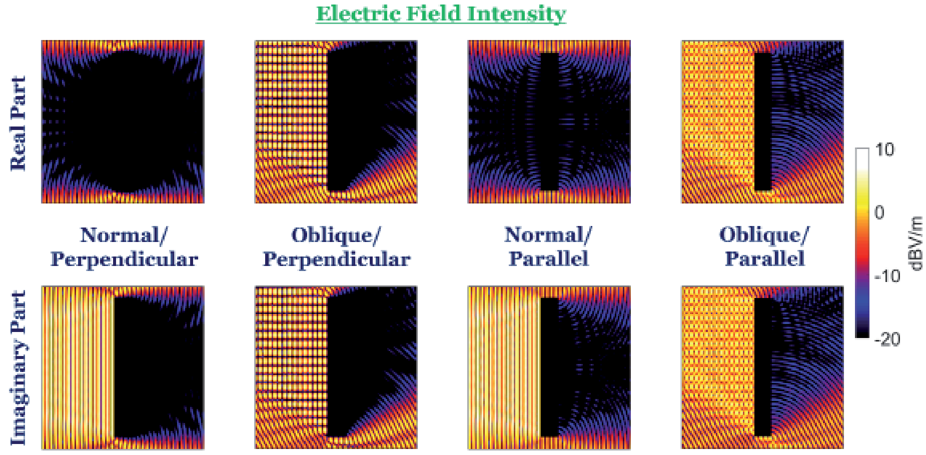

Figure 5. The electric-field intensity distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by various plane waves at 16 GHz.

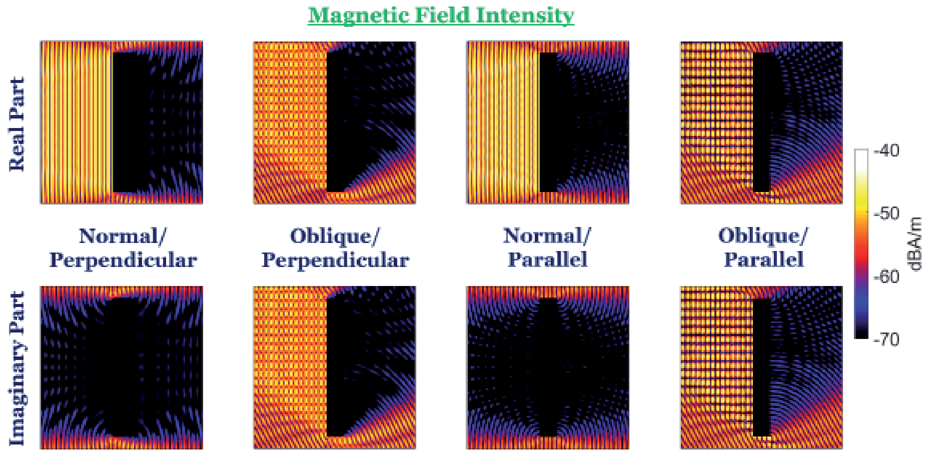

Figure 6. The magnetic-field intensity distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by various plane waves at 16 GHz.

the horizontal direction further showed the existence of standing waves due to reflections. The magnetic-field intensity plots in Figure 4 complemented these observations (dominantly standing waves for the normal incidences and mixtures of traveling and standing waves for the oblique incidences, in the reflection region). Finally, both Figure 3 and Figure 4 clearly demonstrated the effect of polarization on the electromagnetic response of the box.

The results described above were not surprising, and they more or less verified the very basic knowledge of plane waves and their reflection from planar surfaces. Nevertheless, we noted that these solutions were obtained with 1% maximum error (when satisfying Maxwell's equations) for a finite box. For example, diffractions that occurred for both normal and oblique incidences were clearly (and very accurately) observed in Figures 3 and 4. Such diffractions were significant even for the normal-incidence case when the polarization of the electric field was parallel. These accurate results can be beneficial for benchmarking high-frequency techniques.

Figures 5 and 6 present similar results when the frequency was increased to 16 GHz. Once again, real and imaginary parts of the electric-field intensity and the magnetic-field intensity were plotted for four different excitations. Other than more oscillatory patterns, as expected, the plots demonstrated similarities to the corresponding plots in Figures 3 and 4. The normal incidences led to dominantly standing waves, while the oblique incidences led to horizontally standing and vertically traveling waves in the reflection region. Diffractions remained strong, especially for the oblique incidence and parallel polarization, leading to significantly nonzero fields behind the box.

We next considered the simulation results at 32 GHz in Figures 7 and 8. This time, the amplitudes of the electric-field intensity and the magnetic-field intensity, as well as the power density, were plotted. Figure 7 depicts the normal-incidence cases, considering both perpendicular and parallel polarizations. We observed deep shadowing behind the box, as well as interesting effects of diffractions. Results for the oblique incidences are shown in Figure 8, where

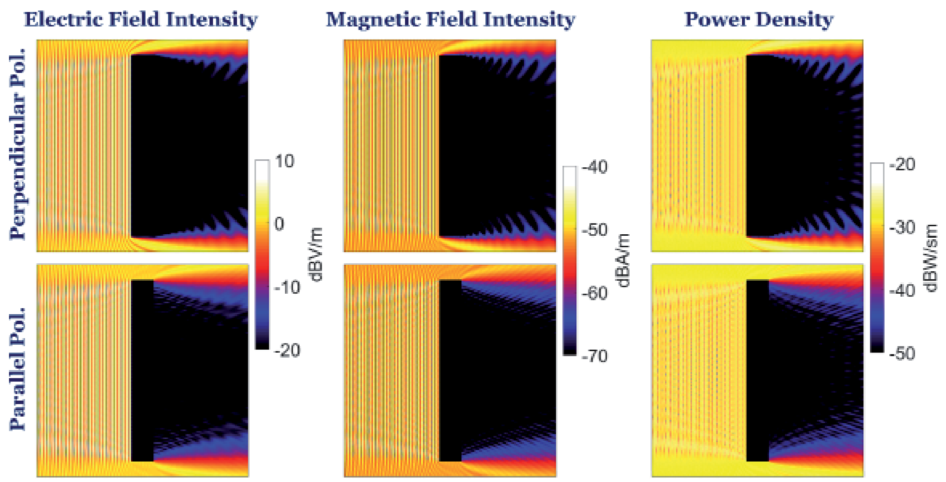

Figure 7. The electric-field intensity, magnetic-field intensity, and power-density distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by plane waves with normal incidences at 32 GHz.

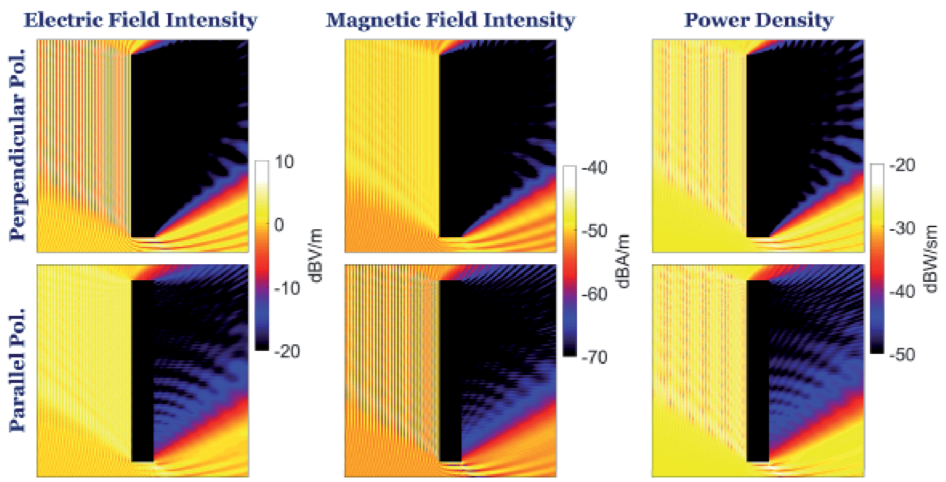

Figure 8. The electric-field intensity, magnetic-field intensity, and power-density distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by plane waves with oblique incidences at 32 GHz.

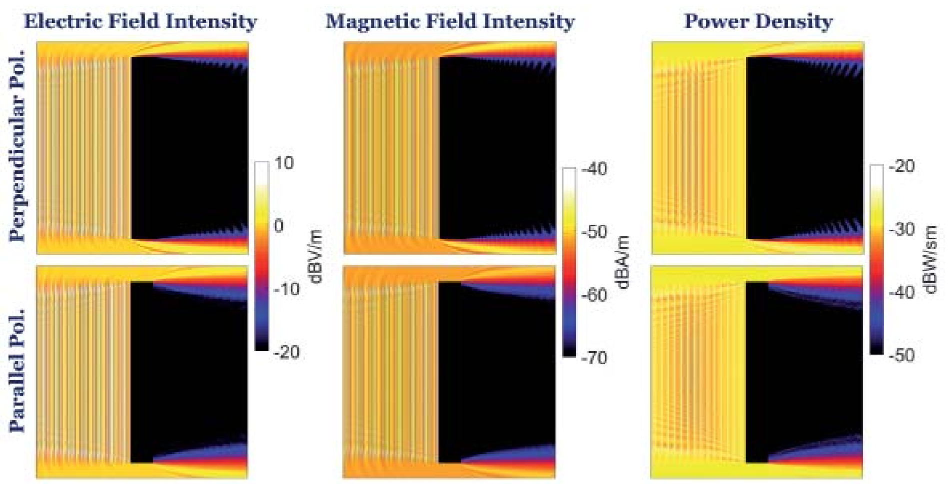

Figure 9. The electric-field intensity, magnetic-field intensity, and power-density distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by plane waves with normal incidences at 64 GHz.

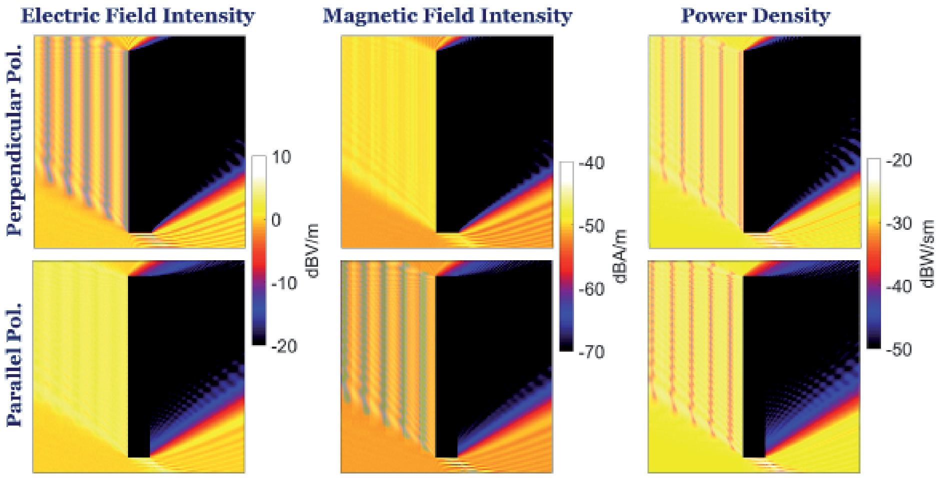

Figure 10. The electric-field intensity, magnetic-field intensity, and power-density distributions obtained for the rectangular box of SOLBOX-18 when it was illuminated by plane waves with oblique incidences at 64 GHz.

the significance of diffractions (especially for the oblique incidence and parallel polarization) was clearly observed.

Finally, Figures 9 and 10 present the corresponding plots when the frequency was increased to 64 GHz. The large electrical size of the box was apparent, with very oscillatory patterns in both reflection and transmission regions. Some artifacts were visible, especially in the oblique-incidence plots, which seemed to be related to the resolution of the images (sampling of near-zone fields), which become insufficient for such oscillatory patterns.

4. References

1. A. K. Bhattacharyya, *High-Frequency Electromagnetic Techniques: Recent Advances and Applications*, New York, John Wiley & Sons, 1995.

2. Ö. Ergül and L. Gürel, *The Multilevel Fast Multipole Algorithm (MLFMA) for Solving Large-Scale Computational Electromagnetics Problems*, New York, Wiley-IEEE, 2014.

Commission E
(Electromagnetic Environment and Interference)

Announcement of a Commission E corner in the Radio Science Bulletin

Commission E announces a corner in the Radio Science Bulletin (RSB) showcasing latest research, news, updates and announcements from different geographical regions. Concise reports, editorially in line with the RSB and subsequent to a review process, would appear in this corner. The details along with an approximate length (maximum) is provided below.

- Updates on activities and latest developments from different geographical regions: Up to 2 paragraphs
- Short report or concise article on recent research and development (novel ideas, implementation, results) – 1 page including figures and plot
- Activities supporting the URSI flagship conferences, collaborations, Commission E promotion-related information – 1 page

The scope of URSI Commission-E includes (but is not restricted to) the following topics:

- Terrestrial and planetary noise of natural origin, seismic associated electromagnetic fields
- Man-made electromagnetic environment
- The composite noise environment
- The effects of noise on system performance
- The effects of natural and intentional emissions on equipment performance
- The scientific basis of noise and interference control, electromagnetic compatibility
- Spectrum management

Contributions can be sent to the following members:

Articles on recent research and development - Kaushal Buch (kdbuch@gmrt.ncra.tifr.res.in)

Updates from different geographical regions - Virginie Deniau (virginie.deniau@ifsttar.fr)

Conferences, collaborations, Comm-E related - Frank Gronwald (frank.gronwald@uni-siegen.de)

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First Things First

On our honeymoon, my wife and I took a bike ride through Shark Valley in Everglades National Park, Florida. While we did not see any sharks, the place was crawling with alligators. As we merrily peddled along, a breeze came through and blew my wife's floppy hat off of her head, and it landed next to the snout of a very large alligator. As we contemplated the situation, my new bride grumbled about how much she loved that hat. Since the alligator did not seem interested in the hat (I came to this conclusion because the alligator did not pick it up and wear it), and since I was in my early twenties and nearly invincible, I ran over and got the hat for her. My wife's happiness was paramount, so I made a move that was aligned with my priorities. Later, at the visitor center, I learned that an alligator can easily outrun a human over a short distance. Interesting fact: maybe my priorities needed realigned.

Our limited bandwidth forces us to prioritize goals and tasks. We have a real-time optimization problem in which our ethics play a critical constraint and weighting on the cost function to be minimized. One approach to prioritization elevates tasks with the highest level of urgency. Urgent tasks with a short time fuse go to the top. However, one pitfall to this approach is that not all urgent tasks are actually important. Another approach to prioritization views tasks through a risk-averse lens: evaluate the consequences associated with not completing a task and elevate tasks with the highest consequences. Yet another approach to prioritization uses a hedonistic approach, in which tasks that bring you the greatest happiness percolate to the top. All of these techniques have pros and cons, so what if instead, you prioritized according to your principles?

Stephen Covey describes a simple approach to prioritization in his book, *The 7 Habits of Highly Effective People*, and a subsequent book, *First Things First: To Live, to Love, to Learn, to Leave a Legacy*, coauthored with A. Roger Merrill and Rebecca R. Merrill. These books present the two-by-two matrix shown in Figure 1, which categorizes tasks based on importance and urgency. The first quadrant, at the intersection of "High Importance" and "High Urgency," consists of tasks that are necessary to complete and have a short time window in which to do so. These are often categorized as crises or pressing problems, and include important work deadlines, or picking up children from daycare. The second quadrant, at the intersection of "High Importance" and "Low Urgency," consists of tasks that are key for reaching goals but do not have a time constraint. These tasks include planning, relationship building, and process improvements. The third quadrant, at the intersection of "Low Importance" and "High Urgency," tend to be distractions, and could include unimportant e-mails and phone calls, interruptions, and minor issues. The fourth quadrant, at the intersection of "Low Importance" and "High Urgency," tend to be time wasters, and could include busy work and excessive escapist activities.

Tasks that are of high importance and are urgent often trump all other tasks, but Covey argues that we should also devote significant time to the "Important, Non-Urgent" quadrant of the matrix. Covey states that focusing on these types of tasks actually reduces the number of urgent, important tasks that tend to lead to high levels of stress, sacrifice, and burn out. As an example, it is easy to reduce the priority of planning for turnover in comparison to other tasks that are directly related to your day-to-day job when you have a fully staffed department. However, as soon as you have turnover, this planning instantly becomes an urgent task. On top of that, the hiring, communication of expectations, and training plan may not be fully thought out or as effective as it would have been had you had the appropriate time and headspace to constructively approach the task.

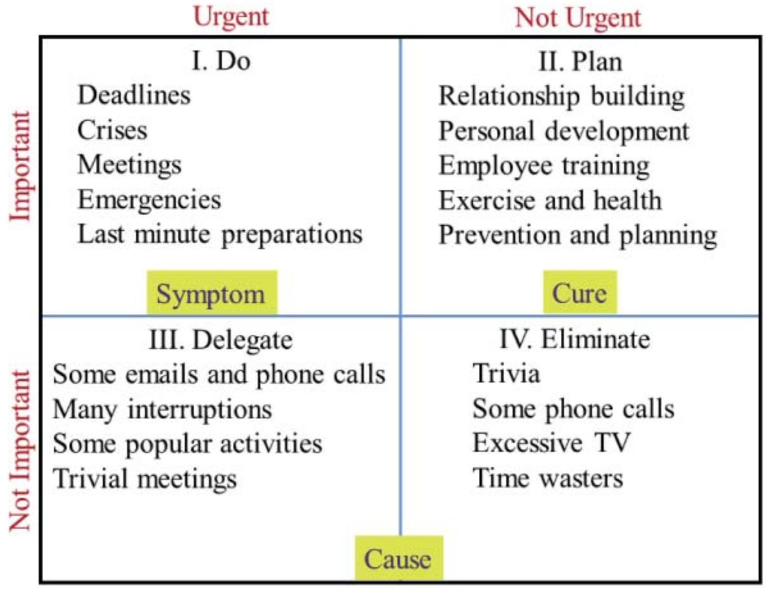

Figure 1. A two-by-two matrix that categorizes tasks based on importance and urgency (taken from books by Steven Covey et al.: see text).

Covey et al. point out that your various roles and principles are as important as a timeline. Approach prioritization with a sense of purpose based on your principles, rather than based on urgency, risk averseness, or hedonistic tendencies. Most of us face conflicts between our personal and professional lives with potential sacrifices and consequences associated with either decision. By using your principles to evaluate the competing priorities, you can gain a sense of clarity about what is most important, which also helps you communicate your justification on the decision to stakeholders (both personal and professional). You spend your time and money on your priorities. If there is a gap between what you say is important to you and how you are using your resources, it is worth reflecting on your principles and reframing how you prioritize back to your moral compass.

The most famous outline of prioritization is likely Maslow's hierarchy of needs. Work deadlines and extracurricular pursuits are trivial when you or your loved ones lack security and a sense of belonging. W. H. Auden gave us an interesting priority: "Thousands have lived without love, not one without water."

Historical Corner Column

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Foreword

One of the main books of electromagnetics (M. Born and E. Wolf, *Principles of Optics, Sixth Edition*, Oxford, Pergamon Press, 1980) reports the following formula at page 87:

$$\alpha = \frac{3}{4\pi N}\frac{\varepsilon - 1}{\varepsilon + 2}$$

$$= \frac{3}{4\pi N}\frac{n^2 - 1}{n^2 + 2},$$

where α is the polarizability of the dielectric nonmagnetic medium, ε is its (relative) dielectric constant, n is its index of refraction, and N is the number of molecules per unit volume. The text then identifies it as the Lorentz-Lorenz relation, but a footnote also reports the names of Clausius and Mossotti. Actually, some texts instead report Lorenz-Lorentz in place of Lorentz-Lorenz, and this matter deserves a little historical investigation.

In this paper, these four scientists – an Italian, Ottaviano Mossotti; a Polish/German, Rudolph Clausius; a Dane, Ludvig Lorenz; and a Dutchman, Antoon Lorentz – are briefly presented. Some insight on how they contributed to this formula is provided, along with comments on the rightful order of the names for the relation.

It is also worth noticing that Lorenz and Lorentz are often mistaken for what concerns the Lorenz retarded potentials and the Lorenz gauge, which are often credited erroneously to Lorentz (J. Van Bladel, "Lorentz or Lorenz?", *IEEE Antennas and Propagation Magazine*, **33**, 2, 1991, p. 69), even in major textbooks, among the many being the one already cited, by Born and Wolf.

The Clausius-Mossotti and Lorentz-Lorenz Relations

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Abstract

This paper focuses on a law of refraction that was discovered independently not by two researchers, not by three, but indeed by four! The law is known as the Clausius-Mossotti law, or the Lorentz-Lorenz law, and was derived either in electromagnetics or in optics, but it is essentially the same. Indeed, extremely scrupulous researchers name it the Clausius-Mossotti-Lorenz-Lorentz formula, but much is to be said about it, starting from the order of the names.

1. The Relation

Whichever name you want to give to it, the relation is a simple relationship stating that the ratio of two polynomials – either first order in the medium permittivity or second order in the index of refraction – is a constant for a given medium. It binds a macroscopic parameter, the permittivity or index of refraction, which has a uniform value all over the medium, to microscopic quantities linked to molecular aspects of the material.

Four different scientists have derived this relation in electromagnetics and in optics, twice in each of these two fields. These scientists will be presented in strict chronological order of birth. About 60 years separate the birth of the oldest, Mossotti, from the birth of the youngest, Lorentz, and yet this is not the order of the key papers published, as we will see.

2. The Scientists

2.1 Ottaviano Fabrizio Mossotti

Readers might be familiar with Ottaviano Fabrizio Mossotti (Novara, Italy, April 17, 1791 – Pisa, Italy, March 20, 1863; Figure 1) due to an article in this same bulletin a few years ago, where this relation was also briefly discussed [1].

In 1836, Mossotti published his first fundamental work on electric induction [2]. This was a paper that was publicly appreciated by Michael Faraday, and that was part of the basis of J. C. Maxwell's development of the displacement current. Indeed, Mossotti was one of the 23 scientists that Maxwell explicitly cited in his 1864 paper [3, 4]. Subsequent studies on this topic led to publication in 1850 of some results obtained in 1846 [5]. In this latter paper, Mossotti studied the effect of the electric field on a dielectric, modeled as a large number of fixed molecules surrounded by a displaceable "atmosphere" of electric fluid. There, he clearly introduced the concept of the polarization of a molecule and even if his mathematical development did not explicitly lead to the equation now known as the Clausius-Mossotti relation, its full concept was in this paper. This paper, [5], was very difficult to follow for the modern reader as already pointed out in [1], since Mossotti was following the "one fluid" electric paradigm that was competing, at the time, with the "two fluids" paradigm.

Figure 1. Ottaviano Fabrizio Mossotti (Novara, Italy, April 17, 1791 – Pisa, Italy, March 20, 1863): A bas-relief from his tomb in the monumental cemetery of Pisa (Italy) (photo by the author).

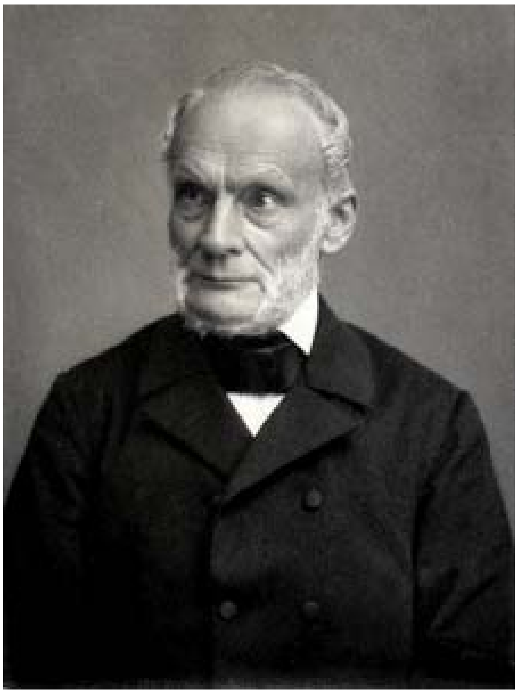


Figure 2. Rudolf Julius Emanuel Clausius (Köslin, Poland, January 2, 1822 – Bonn, Germany, August 24, 1888) (public domain).

Indeed, this latter view prevailed, and even if we do not talk any more of "fluids" or "atmosphere," we still distinguish between two kinds of electric charges: positive and negative.

2.2 Rudolf Julius Emanuel Clausius

Rudolf Julius Emanuel Clausius (Köslin, now Koszalin, Poland, January 2, 1822 – Bonn, Germany, August 24, 1888; Figure 2) was a physicist and mathematician, and a key figure in thermodynamics. His most famous paper, dealing with the mechanical theory of heat, was published in 1850 [6]. In this paper, he reformulated Carnot's principle to overcome a contradiction with the concept of conservation of energy, and restated the two laws of thermodynamics; the second of these got his final statement thanks to him in [7]. In 1865, Clausius gave the first mathematical version of the concept of entropy, and also gave it its name [8].

In a later work, the second edition of the second volume of his mechanical theory of heat, published in 1879 [9], Clausius augmented his previous electrical investigations with new investigations on electrodynamics. In particular, among the new results, he wrote ([9, p. 94] and [1]):

$$K = \frac{1+2g}{1-g}. \tag{1}$$

Clausius indeed derived this in a way very similar to Mossotti, taking into account homogeneous spherical particles. For Clausius, g is the ratio between the volume occupied by the spheres and the total volume, which is of course bound to the relative permittivity of the macroscopic medium, assumed homogeneous, and K is a constant depending on the medium.

In modern form, the Clausius-Mossotti relation is [1]

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{\varepsilon - \varepsilon_0}{\varepsilon + 2\varepsilon_0} \tag{2}$$

$$= \frac{4\pi N_A \alpha}{3} \frac{\rho_m}{M},$$

where ε, ε_r, ε_0 are the absolute and relative permittivity of the medium and of free space, respectively; N_A is Avogadro's number; α is the medium's polarizability; ρ_m is the dielectric density; and M is the molecular mass.

2.3 Ludvig Valentin Lorenz

Ludvig Valentin Lorenz (Helsingør, Denmark, January 18, 1829 – Frederiksberg, Denmark, June 9, 1891; Figure 3) is probably the less known of the four scientists. Indeed, he contributed much to electromagnetics, but his achievements are often credited to the more famous Lorentz (see following section). It was something of a Shakespearian tragedy to be born in Helsingør and to be mistaken with another scientist. Yet retarded potentials in electromagnetics

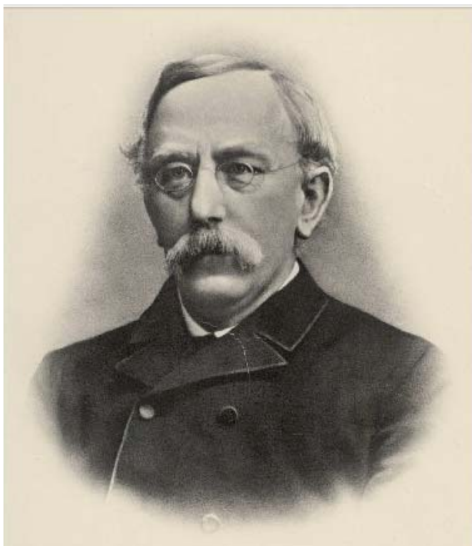


Figure 3. Ludvig Valentin Lorenz (Helsingør, Denmark, January 18, 1829 – Frederiksberg, Denmark, June 9, 1891) (The Royal Library: The National Library of Denmark and Copenhagen University, Creative Commons license).

and the Lorenz gauge condition were published by him [10], even if often they are credited to A. H. Lorentz [11, 12]. Indeed, his work was almost contemporary to Maxwell's *Dynamical Theory*, but he did not use Maxwell's theory, too complex and new, and he based his work on older approaches, such as Kirchhoff's [11, 12].

In 1869, Lorenz established several empirical formulas for the index of refraction, n, giving its variation with temperature and wavelength for some substances with a precision never before attained [13]. Lorenz wrote n according to Cauchy's dispersion formula [14], that is, as a series with coefficients a_i in negative even powers of the wavelength λ:

$$n(\lambda) = m + a_1\lambda^{-2} + a_2\lambda^{-4} + a_3\lambda^{-6} + \ldots, \quad (3)$$

where m is the refractive index reduced at infinite wavelength, that is, $m = \lim_{\lambda\to\infty} n(\lambda)$. By measuring n at two different wavelengths and truncating Equation (3) to the first two terms, he obtained

$$m = \frac{\lambda_1^2 n_1 - \lambda_2^2 n_2}{\lambda_1^2 - \lambda_2^2}. \quad (4)$$

Thanks to his very accurate measurements, he retrieved m and understood that it only depended on the density of the medium, and that the temperature effect was only indirect, due to thermal expansion and consequent density variation.

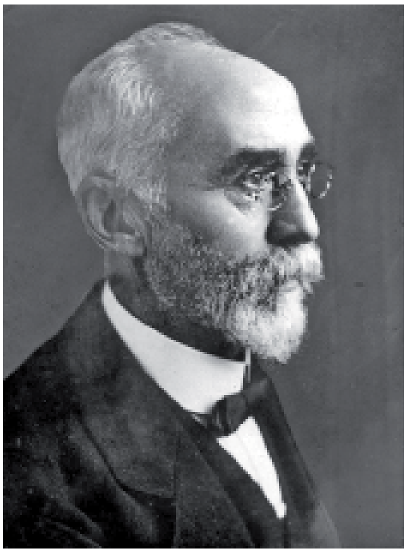


Figure 4. Hendrik Antoon Lorentz (Arnhem, Netherlands, July 18, 1853 – Haarlem, Netherlands, February 4, 1928) (public domain).

Because of this dependence only from density, he then developed

$$\frac{m^2 - 1}{m^2 + 2} v = \text{constant}, \quad (5)$$

where $v = 1/d$ is the specific volume, d being the density. It is important to note that the limit for $\lambda \to \infty$ indeed makes Equation (5) an electrostatic formula, akin to the ideas developed by Mossotti and Clausius.

Further developments, under the hypothesis that the medium was comprised of spherical and optically homogeneous molecules, led to

$$\frac{n^2 - 1}{n^2 + 2} v = \frac{n_i^2 - 1}{n_i^2 + 2} v_i \left(1 + \frac{16}{5}\pi^2 \frac{n_i^2 - 1}{n^2 + 2}\frac{\beta^2}{\lambda^2}\right), \quad (6)$$

where n is the refractive index of the inhomogeneous medium and v its specific volume; n_i and v_i are the corresponding values for the molecules, considered as homogeneous spheres; β is the molecular "sphere of action" radius; and λ is the wavelength. This is particularly interesting, because it bounds dispersion to the inhomogeneity of the medium, without the need for an ether.

Lorenz indeed used Equation (6) for estimating molecular dimensions from dispersion measurements. This was indeed approximate, since he understood the limitation due to the hypothesis of sphericity of the molecules. Indeed, β was defined by him as the radius of the sphere in which light propagation was effectively influenced by the molecule, and not the physical radius (it must be remembered that atomic and molecular theory was in a very early stage then).

2.4 Hendrik Antoon Lorentz

Hendrik Antoon Lorentz (Arnhem, Netherlands, July 18, 1853 – Haarlem, Netherlands, February 4, 1928; Figure 4), is finally not only the youngest but also the most famous of the four.

On November 17, 1877, at only 24 years of age, Hendrik Antoon Lorentz was appointed to the newly established chair in theoretical physics at the University of Leiden. During his first twenty years in Leiden, Lorentz was primarily interested in the electromagnetic theory of electricity, magnetism, and light. After that, he extended his research to a much wider area while still focusing on theoretical physics. His most important contributions, besides electromagnetism, were in the areas of electron theory and relativity.

Lorentz theorized that atoms might consist of charged particles, and suggested that the oscillations of these charged particles were the source of light. When a colleague and former student of Lorentz's, Pieter Zeeman (Zonnemaire, Netherlands, May 25, 1865 – Amsterdam, Netherlands, October 9, 1943), discovered the Zeeman Effect in 1896, Lorentz supplied its theoretical interpretation. This experimental and theoretical work earned both the Nobel Prize in Physics in 1902.

Back to the focus of this article, Lorentz developed his formula in 1877-1878 [15]. His view was electromagnetic, not optical, much in Mossotti's view, inasmuch he imagined molecules embedded in a dielectric ether. This was somewhat bizarre, since the "other" Lorenz had previously dismissed the idea of ether as "unphysical" [10], and completely avoided it.

After the early 1878 development, Lorentz found the expression [16]

$$\frac{n^2-1}{(n^2+2)d}=\frac{4\pi\rho^3}{3m}\frac{(3+4\pi\varepsilon_0)-4\pi\varepsilon_0\frac{\rho^3}{\chi}}{(3+8\pi\varepsilon_0)\frac{\rho^3}{\chi}-8\pi\varepsilon_0}, \tag{7}$$

where ε_0 is the dielectric constant of the ether; m is the mass of the spherical molecules of radius ρ; χ is the ether's specific resistance as defined by Helmholtz, that is, a coefficient responsible for optic losses when light travels into a medium. χ is conceptually bound to a resistance that the – fixed – molecules of matter exert on the vibrating ether.

Lorentz, not being an experimental physicist, did not perform any measurements of his own, but compared Equation (7) with results in the literature, finding good agreement [16].

3. Timeline and Differences

The graph in Figure 5 can be drawn, summarizing the previous section. To better fix these events in the electromagnetic timeline, J. C. Maxwell's lifespan and his two main contributions, the *Dynamical Theory* [3] and the subsequent *Treatise* [17], are reported.

Our focus formula is now most often written, in modern notation, in one of the two forms:

$$\frac{\varepsilon_r-1}{\varepsilon_r+2}=\frac{4\pi}{3}\alpha, \tag{8}$$

$$\frac{n^2-1}{(n^2+2)}=\frac{4\pi}{3}\alpha.$$

Since in a non-magnetic dielectric material it is true that $n=\sqrt{\varepsilon_r}$, in such a medium the two equations are indeed the same.

The equation links a macroscopic, classical electromagnetics and optics quantity, the relative permittivity or the square of the index of refraction, to a microscopic quantity, the polarizability, α, of the substance.

Lorentz himself stated that the formulas are the same, as the excerpt from [18] in Figure 6 shows. There, Lorentz recognized that $n^2=\varepsilon_r$ (in his notation, the refractive index was μ, and it must be noted that Lorentz, as did many others, used the flavor of the CGS system where $\varepsilon_0=1$ [19] – as is clearly understandable by Equation (208) on page 142 of [18] – and hence when he writes ε, the modern reader should understand ε_r).

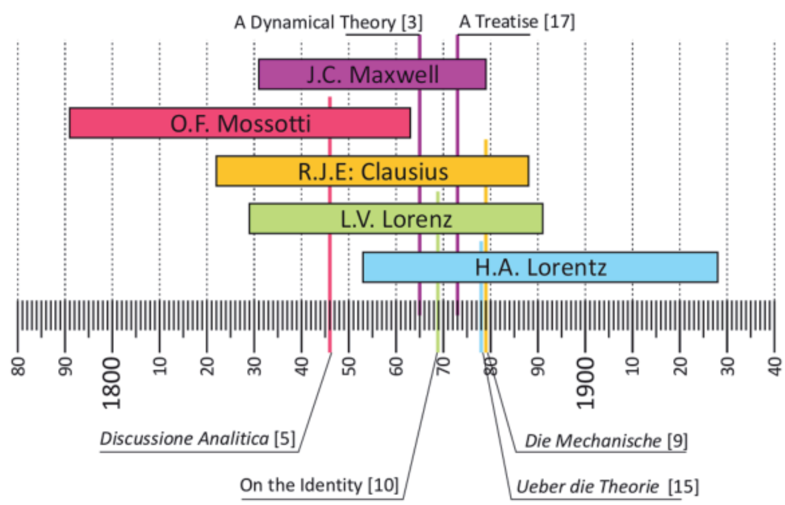
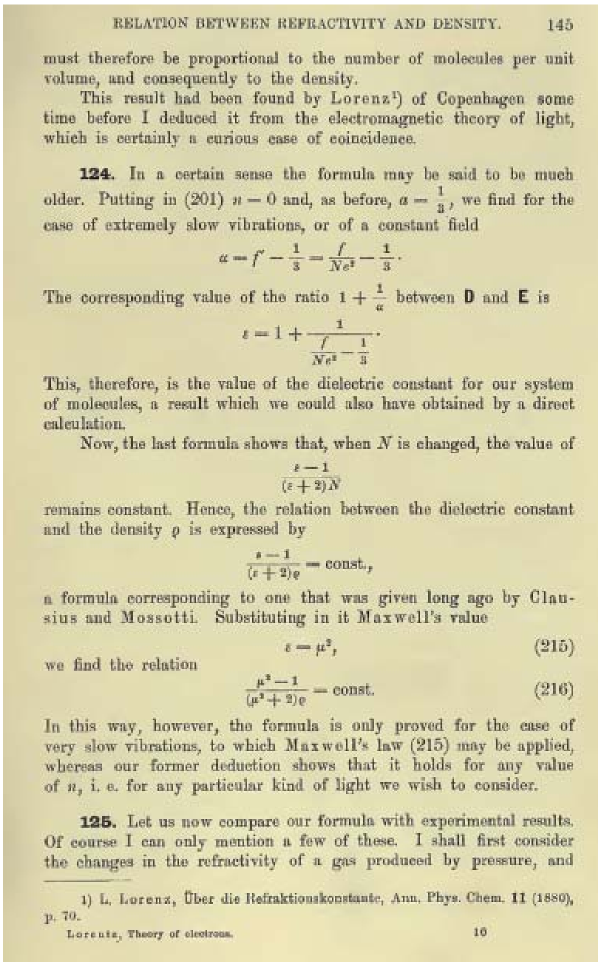


Figure 5. A timeline of the life spans of O. F. Mossotti, R. Clausius, L. V. Lorenz, H. A. Lorentz, and J. C. Maxwell, also showing the key papers dealing with the relation.



RELATION BETWEEN REFRACTIVITY AND DENSITY. 145

must therefore be proportional to the number of molecules per unit volume, and consequently to the density.

This result had been found by Lorenz[1]) of Copenhagen some time before I deduced it from the electromagnetic theory of light, which is certainly a curious case of coincidence.

124. In a certain sense the formula may be said to be much older. Putting in (201) $n = 0$ and, as before, $a = \frac{1}{3}$, we find for the case of extremely slow vibrations, or of a constant field

$$\alpha = f' - \frac{1}{3} = \frac{f}{Ne^2} - \frac{1}{3}.$$

The corresponding value of the ratio $1 + \frac{1}{\alpha}$ between **D** and **E** is

$$\varepsilon = 1 + \frac{1}{\frac{f}{Ne^2} - \frac{1}{3}}.$$

This, therefore, is the value of the dielectric constant for our system of molecules, a result which we could also have obtained by a direct calculation.

Now, the last formula shows that, when N is changed, the value of

$$\frac{\varepsilon - 1}{(\varepsilon + 2)N}$$

remains constant. Hence, the relation between the dielectric constant and the density ρ is expressed by

$$\frac{\varepsilon - 1}{(\varepsilon + 2)\rho} = \text{const.},$$

a formula corresponding to one that was given long ago by Clausius and Mossotti. Substituting in it Maxwell's value

$$\varepsilon = \mu^2, \tag{215}$$

we find the relation

$$\frac{\mu^2 - 1}{(\mu^2 + 2)\rho} = \text{const.} \tag{216}$$

In this way, however, the formula is only proved for the case of very slow vibrations, to which Maxwell's law (215) may be applied, whereas our former deduction shows that it holds for any value of n, i. e. for any particular kind of light we wish to consider.

125. Let us now compare our formula with experimental results. Of course I can only mention a few of these. I shall first consider the changes in the refractivity of a gas produced by pressure, and

1) L. Lorenz, Über die Refraktionskonstante, Ann. Phys. Chem. 11 (1880), p. 70.

Lorentz, Theory of electrons. 10

Figure 6. Part of page 145 of Lorentz's book [18], where he recognized that the formula he derived was already derived by Lorenz (top of the page) and that the Clausius-Mossotti relation was essentially the same (Equation (215)) (copyright expired).

What then is the difference? It is just a matter of the model these four scientists had in mind when dealing with the microscopic part. All of them considered matter as composed of molecules. Mossotti believed in a one-fluid paradigm, while the other three considered two types of charges, positive and negative. Lorenz was not considering aether, while Clausius and Lorentz did, and the second introduced a friction term for ether with which he explained losses. Clausius, as stated before, was similar to Mossotti, but his paradigm considered two kinds of electric fluids, in absolute motion, hence needing a fixed aether [20]. We must remember that the concept of the electron as a charged particle started to be seriously considered in the eighties of the XIX century, with the 1892 paper where the Lorentz force was introduced [21] and its full development [22], up to the key experiment by Thompson in 1896 (published the following year in [23]).

Indeed, due to the lack of a more refined model, all of them considered the molecules as ideal spheres, and Lorenz in particular assigned an index of refraction to these spheres, which was then diluted, since molecules were separated by free space in his model. However, molecules cannot, of course, be considered as spheres in a modern paradigm and, indeed, Equation (8) appears so much "simpler" than Equations (6) and (7) because the complexity that is blatantly shown there is hidden in the polarizability, α, which is a quantity peculiar to each molecule.

4. The Name

However, what is the name? Let us see Figure 7. This is a Google Ngram, a search on all books scanned by Google for a given term. Sadly, Google does not include books scanned after 2008, but the graph is interesting anyway. It reports the occurrences of the terms "Clausius-Mossotti," "Lorenz-Lorentz," and "Lorentz-Lorenz." The term "Mossotti-Clausius" is *never* found, while the term holding all four names could not be searched due to the system's limitations. The vertical scale would have shown the frequency – in percentage – of the occurrences of the terms on all the books, which has no real meaning for us, the relative height of the curve being most important. What is relevant is that, indeed, no one apparently used "Mossotti-Clausius," and that "Lorentz-Lorenz" was definitely more common than "Lorenz-Lorentz."

Figure 7. Google Ngram: The frequency in Google-scanned books of the three main ways of naming the formula.

However, strictly speaking, if the chronological order of the publications were to be used, the terms would be "Mossotti-Clausius" and "Lorenz-Lorentz," if we wish to keep the two formulas separated, or "Mossotti-Lorenz-Lorentz-Clausius," if we recognize that it is indeed just one formula [24, 25, 26].

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US FCC Affirms its Current Safety Limits For RF Radiation and 5G Wireless

Citing support of the Food and Drug Administration's (FDA) Center for Devices and Radiological Health (CDRH), the United States' Federal Communications Commission (FCC) announced in December, 2019, that it reaffirmed the radio-frequency (RF) radiation exposure limits that it had first adopted in 1996 [1]. The action was undertaken in the face of appeals from some to tighten and others to loosen the existing limits.

In the process, the FCC also resolved and terminated a 2013 notice of inquiry that sought public input on whether it should modify its existing RF exposure rules considering recent scientific opinions and authoritative expert views, among other issues [2]. Apparently, six years since its notice of inquiry, the FCC deemed it appropriate to maintain the existing RF exposure limits. It is interesting to observe that the FCC declined to make changes that would stiffen the current rules or to make any changes that would effectively relax the current rules.

Note that the FCC exposure limits are currently specified up to 100 GHz. These limits could in principle be applied to the millimeter waves used for 5G services and for future uses of wireless technologies at even higher frequencies and, in fact, the FCC has signified as such. In the recently released Notice of Proposed Rulemaking, and Memorandum Opinion and Order [2], the FCC is proposing to formalize additional limits for localized RF exposure from devices operating at higher GHz frequencies and to extend this to terahertz (THz) frequencies. It proposed to extend the same constant exposure limits that presently apply from 6 GHz to 100 GHz up to an upper frequency of 3,000 GHz (3 THz), which is commonly regarded as the upper bound of the RF bands.

Newer technologies that employ techniques such as adaptive array antennas and beamforming create complex electromagnetic fields that present challenges for current RF measurement methods. The FCC's RF exposure rules do not yet specify a metric or spatial maximum power-density limit for localized exposure at higher frequencies. As wireless devices and systems are being developed for operation at higher frequencies for future 5G services in the millimeter-wave bands, the FCC appears ready to propose a general localized power density exposure limit above 6 GHz of 40 W/m^2 averaged over 1 cm^2 for the general population or uncontrolled exposure, applicable up to the upper frequency boundary of 3 THz. The FCC is currently inviting comments on this proposal [2].

The RF and microwave exposure rules established by the FCC are based on specific absorption rate (SAR) and maximum permissible exposure (MPE) limits [3, 4]. SAR is the accepted metric or quantity that corresponds to the relative amount of RF and microwave power deposition to or energy absorption in a portion of or for the whole body, such as any part of a user of a wireless device or mobile-phone handset, or the entire body in the radiation domain of a Wi-Fi antenna or base station. The basic restrictions for human exposure are defined by SAR limits. MPE limits are derived from the SAR limits, in terms of free-space field strength and power density.

For exposures from mobile-phone-related operations, the FCC specifies a quantity of local tissue SAR of 1.6 W/kg, as determined in any one gram (1 g) of body tissue. An average value of 0.08 W/kg in any 1 g of body tissue was also set for whole-body exposures.

The FCC rules impose basic restrictions on SAR limits for the general public, and occupational exposures to avoid whole-body heat stress and excessive localized tissue heating, specifically to prevent biological and health effects in response to an induced body temperature rise of 1°C or more for an averaging time of 6 min [3, 4]. This level of temperature increase results from exposure of individuals under moderate environmental conditions to a whole-body SAR of approximately 4 W/kg for about 30 min. A whole-body average SAR of 0.4 W/kg was chosen as the restriction to provide protection for occupational exposure. An additional reduction factor of five was introduced for public exposure, giving an average whole-body SAR limit of 0.08 W/kg. This value was purposefully relaxed by a factor of 20 to permit a maximum local tissue SAR of 1.6 W/kg.

The power-density limits or MPE applicable to the general population and occupational exposure for 1.5 GHz to 100 GHz are 10 W/m^2 and 50 W/m^2 , respectively, for whole-body continuous exposure.

According to the FCC, over 1,000 comments and representations were filed in response during the six years since the 2013 Notice of Inquiry. It is not surprising to learn that some of the filings urged the FCC to tighten the RF exposure limits, while others asked for less-restrictive limits.

Supporters for stricter RF guidelines included the American Academy of Pediatrics, American Academy of Environmental Medicine, California Brain Tumor Association, Center for Family and Community Health, Electromagnetic Radiation Safety, and International EMF Scientist Appeal, among others. They called on the FCC to adopt stronger exposure limits on RF radiation exposure. Many also implored the FCC to impose a moratorium on the wireless industry to pause its deployment of 5G services. The stated reason was that more research was needed on account of the paucity of scientific knowledge regarding the effects on human health from the much higher RF frequencies and the impact of the ubiquity of small-cell base stations dictated by 5G deployment.

Among advocates for the FCC to adopt weaker regulatory limits on RF radiation were submissions from CTIA – The Wireless Association, Mobile Manufacturers Forum, Telecommunications Industry Association, and consultants for the wireless industry. Many of the same petitions also contended that the scientific evidence to date suggests that in terms of causing health effects, 5G is no different from any other cellular mobile technology and systems deployed to date. Arguments were presented for weakening mobile phone RF exposure limits to peak, local SARs at 2 W/kg, averaged over 10 g of tissue (the FCC limit is 1.6 W/kg over 1 g). As a matter of fact, the larger averaging mass would make the limits less stringent by a factor of two or more.

More specifically, some of the submissions also expressed opposition to the requirement that mobile phone retailers warn customers about the possible radiation dangers of holding the phones close to their bodies. In this regard, it is noteworthy that recently [5] the US Supreme Court rejected a challenge filed by CTIA - The Wireless Association against the “cell phone right to know” law adopted by the City of Berkeley, California, in May, 2015 (see http://bit.ly/berkeleymedia).

The city’s ordinance took effect in 2016. It requires dealers to notify their customers of the FCC’s RF radiation standards for mobile phones, and that RF exposure “may exceed the federal guidelines” if users carry their phone in a shirt or pants’ pocket or tucked into a bra while they are connected to a wireless network. Furthermore, retailers must display the warning on a poster or in a handout flyer attributed to the City of Berkeley.

However, the FCC did accede to treating the pinnae (outer ears) like other extremities of the body for purposes of determining compliance with the FCC’s RF exposure limits, irrespective of petitions that appealed otherwise. As extremities, the pinnae – along with the hands, wrists, feet, and ankles – are subject to less-stringent localized RF exposure limits than the rest of the body. For these parts of the human body, the peak spatial-average SAR limit for general-population exposure is set at 4 W/kg, averaged over any 10 g of tissue.

It is significant to note that in affirming treatment of the pinnae as extremities, and through associated comments, the FCC has acknowledged that its RF radiation exposure limits are based solely on localized thermal effects. The FCC also refused to recognize that the pinnae are contiguous to the head, unlike the hands, wrists, feet, and ankles. Any RF-induced field will directly impact the head and brain.

More so, as mentioned above, the larger averaging mass would make the exposure limits less stringent by a factor of two or more for local SARs averaged over 10 g of tissue. The 4 W/kg SAR averaged over 10 g would thus be equivalent to a 1 g SAR of 8 W/kg to 12 W/kg in the pinnae or external ear, which would cause excessive local tissue temperature elevation, which would be easily masked by a 10 g SAR. Moreover, the mass of the pinnae is about 10 g and is geometrically jagged and uneven, which would further accentuate SAR and temperature disparity in causing localized thermal effects.

Recent scientific results on the correlation of SAR with induced tissue temperature elevation and their dependence on the mass of averaging tissue and exposure duration showed that in general, SAR provides a better correlation with temperature elevation for exposure durations between

1 and 2 min (short durations) for most frequencies in use for current wireless technologies [6, 7]. In this case, a mass of 1 g is optimal, but the correlation coefficient remains above 0.9 at 2 min for a 2 g mass.

For longer exposures, the maximum correlation coefficient is reduced, and the correlation favors larger averaging mass. At steady-state (30 min), the correlation of temperature increase with SAR is maximum for a mass of 5 g to 9 g for frequencies below 6 GHz.

However, for exposures at higher GHz frequencies (millimeter waves and 5G), RF energy absorption tends to be more superficial and concentrated. Energy deposition could quickly occur in a smaller tissue area or mass to cause intense temperature elevation within a very short-exposure time period.

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Introduction

So far, I have introduced active female researchers in this column. I have met most of them as colleagues at conferences or through collaboration. It thus has been quite easy to recruit them, but I do not always succeed. I have also lately been contacted by people who had read the column and recommended other interesting scientists in our field. Radio science has been very male dominated from the beginning, and there have not been many active women in the early 1900s who are still remembered, but there exist several very interesting lives' work.

Wars have, in their brutal way, been promoters of new technology. Radars showed their important role during World War II at many frontiers. Since the men were at war, technically capable women had to take over some traditionally male tasks at the home frontiers. Some of them showed extremely good capacity, such as Joan Clarke and many others as code-breakers at Bletchley Park.

In this column, we now present another remarkable female scientist, Dr. Elizabeth Alexander. In a short time, she made important contributions in both her major subject of geology, in Singapore, and in radars as scientific instruments, while employed as Head of Operations Research at the Radio Development Laboratory in New Zealand, during the war. This article was written by Elizabeth Alexander's daughter, Mary Harris, based on her biography [1] of her mother.

Elizabeth Alexander: An Extraordinary Scientist

Mary Harris

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Elizabeth Alexander (Figure 1) was an extraordinary scientist. She changed thinking in two separate sciences, and then disappeared from history. It happened because of the second world war in the Far East.

Elizabeth Caldwell had left Cambridge University in 1935 with a PhD in geology, but remained a good physicist from her first degree there in natural sciences. In 1936, she moved to Singapore, where her husband, Norman Alexander, a New Zealander whom she had met at Cambridge, took up the post of Professor of Physics at Raffles College. In Singapore, Elizabeth had no formal status because she was only a professor's wife, but she began her own research into the geology of the island. She became interested in some of the processes and products of the weathering of rocks under tropical conditions. It seemed as if products of weathering were not just washed away, but were reforming as fresh, hard rock, rather quickly. She set up an experiment, burying particular pieces of rock in mangrove swamp and keeping controls in the laboratory she had made in her own home.

Figure 1. Elizabeth Alexander.

At the same time, and for their own amusement, the Alexanders made themselves a terrestrial globe about 1.2 meters in diameter. They had almost finished it when Elizabeth happened to meet an old school friend while shopping in Singapore. The friend had married a Royal Navy officer in the Hydrographic Service at Singapore Naval Base. There the Admiralty, the governing body of the Royal Navy, was setting up a network of radio-direction-finding stations covering the Indian and Pacific Oceans, and centered on Singapore. The Navy was using traditional Mercator charts for plotting bearings within this network, but it turned out to be quicker to take direct readings from the Alexanders' globe, and just as accurate. The Navy therefore requisitioned the globe, and employed Elizabeth to work on the statistics of bearings that did not meet at a single point. However, the work developed quickly, and she soon became more involved in more technical aspects of radio direction finding (RDF) itself. At that time, the new technologies of radar were also called RDF, for the sake of secrecy.

In 1940, when WWII had started in Europe but not yet in the Far East, Elizabeth went on leave to New Zealand with Norman and their two children. There, she found that New Zealand was well ahead in the development of radar for both home use and Pacific Ocean defenses. Much of the work was in the hands of physicists who had been students at Lord Rutherford's Cavendish Laboratory at Cambridge, at the same time as she and her future husband. There had also long been close links in the intelligence services between Singapore and New Zealand, and the New Zealand Navy itself was still a squadron of the Royal Navy.

On her return to Singapore in 1940, Elizabeth became more heavily involved in RDF at the Singapore Naval Base. In December 1941, the Imperial Japanese Army attacked Pearl Harbor, Hong Kong, the Philippines, Thailand, Malaya, and Singapore, and began its swift progress down the Malay Peninsula towards Singapore. In January 1942, Elizabeth was ordered by the Royal Navy to evacuate her now three children to her husband's family in New Zealand, and return to the Singapore Naval Base with specialist equipment being made in Australia. However, Singapore surrendered soon after she arrived in New Zealand, and she was stranded with her small children, with no news of Norman and no income. Her work in Singapore was known both to New Zealand's intelligence services and radar physicists, and she was invited to set up – from scratch – and run the Operations Research Section of New Zealand's secret radar research unit at its Radio Development Laboratory, the cover name for radar. During her nearly four year's work there and almost in passing, Elizabeth made the interpretation that an anomalous "radar" signal, picked up by a Royal New Zealand Air Force station on Norfolk Island, was in fact coming from the sun. This became the beginning of radio astronomy in Australia, for New Zealand itself did not continue with the research. At the time, Norfolk Island, though nominally Australian, was within New Zealand's wartime region of control, under boundaries set by the USA.

In 1948, reunited with Norman – and with her children left in the care of her sister in England so that they could go to school there – Elizabeth returned to Singapore to help in its recovery from enemy occupation. At first she worked as temporary Registrar, as Raffles College became the University of Malaya in processes held up by the war, and gave personal support to students traumatized by the occupation. In 1949, and then working as geologist again, she was appointed by the Singapore Government to survey the whole island for sources of granite for reconstruction. In this work, which included the first reasonably accurate geological map of the island (still in use), she was able to pick up on her own pre-war research in tropical weathering, and to develop her second contribution to changing thinking in the sciences. Although her own geological laboratory had been stripped bare at the end of the occupation of Singapore, it was possible to retrieve some of her buried samples, and to develop her theory that fresh rock was growing from the products of weathered rocks at previously unrecognized speed. However, her work was again interrupted by Norman's appointment to the professorship of physics at University College Ibadan, Nigeria, where at last he was able to do some research of his own, during the International Geophysical year of 1958. Elizabeth continued to work as "the only geologist on the island of Singapore," but by airmail from Nigeria. In this way, she was able to give advice on tropical soils, on preventing the quarrying out of what later became Singapore's Bukit Timah Nature Reserve, and on work she had started herself in Singapore on improving its water supplies. However, in December 1958, just before her 50th birthday, and worn out with the stresses of the war, she suffered a cerebral hemorrhage and died. Her work on tropical weathering was published posthumously, and her secret work on South Pacific radars simply faded from history.

During Elizabeth's time in New Zealand, she kept a personal diary, written as an extended letter to Norman in internment in Singapore, so that he would know about the life of his family when they met again. I am one of their daughters. Elizabeth's diary came into my possession in the 1990s, at about the time that the New Zealand government declassified its own Radar Narrative, written from reports made during the war. Between them, these two previously unpublished documents fill a gap in New Zealand's own highly significant history of radar developments in the South Pacific. It was obvious to me that I must write Elizabeth's biography [1].

For a full biography of such a scientist, much research was necessary so that her contributions could be placed in several contexts at the same time. Firstly, it was necessary to record enough of the history of the two separate sciences to reveal the significance of the changes to thinking that she made. War is a great motivator for science, and Elizabeth's life covered the effects of the first world war, the politically charged period following it, and the urgencies of the second world war. It was therefore necessary to weave the political and military contexts through those of the sciences. However, there is a third issue in writing about the fall of Singapore to Japan in 1942, because the literature is still dominated by what Prof. Mary Beard aptly called "Big Books By Blokes about Battles." There is no need for feminist aggression in challenging this dominance. My main aim in writing this biography was not only to reveal the contributions to science of a particular woman scientist, but to redress the lack of balance as I went along by putting back into the literatures from which they should never have been excluded many other women scientists. At the same time, it was necessary to ensure that the work was properly academic so I have justified all I have written by references. However, it is never necessary for academic writing to be turgid, so my greatest aim was to make the book comfortably readable, too.

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Report on International Radar Conference (IRC-2019)

The International Radar Conference (IRC) takes place every five years in France. It is organized by the SEE (Société de l'Electricité, de l'Electronique) in the framework of the international relations set up between the IET (Institution of Engineering and Technology), the AESS (IEEE Aerospace and Electronic Systems Society), the IEEE (Institute of Electrical and Electronics Engineers), the CIE (Chinese Institute of Electronics), the IEAust (Institute of Engineers Australia, and the SEE.

For its 2019 edition (held September 23-27, Figure 1), the conference took place in Toulon, France, a typically Mediterranean city. The Palais de Congrés is located at the outskirts of the old city. For centuries, Toulon has had a naval dockyard that generated numerous industries and research laboratories in addition to its own activities.

Such a periodic event presents two focuses: i) dealing in depth with up-to-date themes; and ii) presenting the opportunity to underline new topics on theoretical aspects or stand-out applications.

From the opening plenary session, chaired by François Le Chevalier, present-day topics came to the fore: artificial intelligence (AI) and UAS (unmanned aerial systems). In this session, a large range of subjects was discussed: "Radar and Artificial Intelligence," by David Sadek (Thales); "Radar Technical Challenges, From Decameter to Centimeter Wavelength," by Philippe Dreulliet (ONERA); "Scattoremeter from Space: Seas of Radar Opportunities," by A. Stoffeleen (KNMI); "Wideband Radar," by Prof. Long Teng (Beijing Institute of Technology); "100 kg-Class X-Band Synthetic Aperture Radar Satellite System for On Demand Observation," by Seiko Shirasaka (Keio University). The presentation by F. Boyer (University of Nantes), "Artificial Electric Sense for Underwater Robotics: State of the Art and Perspectives," gave an interesting example illustrating the fact that the activity "detection" is founded on physical phenomena, sometimes quite original.

The subjects on the theme of detection/discrimination of unmanned aerial systems were numerous and diverse. They showed that detection in particular remains difficult, since the environments that have to be taken into account are very diverse from urban environments to differentiation with birds. Some more time will be needed to see efficient and feasible solutions taking shape, perhaps associated with optical and/or multi-spectral systems.

Among the many other sessions deserving to be mentioned were:

- Non-conventional SAR imaging systems
- Low-frequency radars
- Remote sensing from space
- Advanced beamforming
- Automotive applications
- Radar advanced technologies
- Sea clutter
- Passive radar for UAV detection
- Emerging radar applications

Figure 1. The banner of the 2019 International Radar Conference

A well-established tradition is to organize a "historical" session. This one was co-chaired by Yves Blanchard and Simon Watts. Even if it was not a piece of epistemology, it had the merit to remind us i) that experience is indispensable, and ii) that it was always possible over time to find ad-hoc techniques to make projects successful.

The two technical visits proposed by DGA (Délégation Générale pour l'Armement) and Thales Alenia Space as the conclusion of the congress doubtlessly gave a special luster to the event. These were preceded by several tutorials, synthesizing the most recent topics that occurred in the field of radar.

It was certainly satisfying to note the presence of many young participants. The poster sessions advantageously reflected this dynamic aspect.

Three subjects were unfortunately not discussed: propagation, the necessary conditions to access the frequency spectrum, and the use of passive frequency bands, the protection of which could pose problems at the WRC 2019. It has to be kept in mind that three services are entitled to make observations in these passive bands: two space services, the Earth Exploration Satellite Service (passive) and the Space Research Service (passive observation), and one terrestrial service, the Radioastronomy Service. This is all the more regrettable, since WRC 2019 (October 28- November 22, 2019, at Sharm El-Sheik, Egypt) took place right after the conference, during which the competition between detection (active and passive) and radio communications figured among several points of the agenda.

It is understandable that the organizers wished to "dematerialize" documentation at the conference. However, this should not result in a suppression of important information. It was symptomatic that even the composition of the organizing committee and the scientific committee were not made public. It is to be recalled that the scientific committee was responsible for selecting presentations.

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IUCAF 2019 Annual Report

1. Introduction

The Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science, IUCAF, was formed in 1960 by its adhering Scientific Unions, IAU, URSI, and COSPAR, at the behest of URSI. The IUCAF brief is to study and coordinate the requirements of radio-frequency spectrum allocations for passive radio sciences – radio astronomy, space research, and remote sensing – and to make these requirements known to the national and international bodies that regulate the use of the radio spectrum. IUCAF operates as an Inter-Disciplinary Body under the auspices of the International Science Council (ISC, formerly ICS and ICSU). IUCAF is a Sector Member of the International Telecommunication Union's Radiocommunication Sector (ITU-R), with observer status at the Space Frequency Coordination Group (SFCG). IUCAF is celebrating the 60th anniversary of its founding during 2020.

IUCAF is online at http://www.iucaf.org.

2. Membership and Member Affiliations with Other Bodies

There was no change to the composition of IUCAF during 2019. IUCAF is still seeking a replacement IAU committee member for one who resigned in 2018. At the end of 2019, the IUCAF membership from the three adhering Unions was as given in Table 1.

Additionally, the Counselor for ITU-R Study Group 7 (Science Services), Mr. Vadim Nozdrin, is an ex-officio member by virtue of his ITU-R position, as specified in IUCAF's Terms of Reference. IUCAF also has an informal group of correspondents in order to improve its global geographic representation and for consultation on specific issues, for instance, concerning astronomical observations in the optical and infrared domains.

IUCAF member van Driel recently stepped down from CRAF, the European Committee on Radio Astronomy Frequencies of the European Science Foundation (https://www.craf.eu/) whose members include Tiplady. Zhang is Secretary of the Radio Astronomy Frequency Committee in the Asia-Pacific region (RAFCAP), whose members also include Ohishi and Tzioumis (see http://www.atnf.csiro.au/rafcap/). Tzioumis is Chair of ITU-R Working Party 7D (Radio Astronomy). Ohishi, IUCAF's immediate Past Chair, is the official liaison between the IAU and the ITU, and President of IAU Commission F3 (Astrobiology). He recently was appointed Head of the newly-created Spectrum Management Office at the National Astronomical Observatory of Japan. Van Driel is Secretary of IAU Commission B4 on Radio Astronomy, and a member of its Organizing Committee. Liszt is a member of the American Astronomical Society's Committee on Light Pollution, Radio Interference, and Space Debris, and of the IAU Executive Committee on WG Dark and Quiet Sky Protection, and serves on the Steering Committee of the IAU Inter-Division Commission C.B4 on Protection of Existing and Potential Observatory Sites.

Table 1. The IUCAF membership at the end of 2019

URSI	Dr. Haiyan Zhang	China
	Dr. Steven Reising	USA
	Dr. Ingemar Häggström	Sweden
	Dr. Anastasios Tzioumis	Australia
	Dr. Wim van Driel	France
IAU	Dr. Harvey Liszt (Chair)	USA
	Dr. Masatoshi Ohishi	Japan
	Dr. Adrian Tiplady	South Africa
COSPAR	Dr. Yasuhiro Murata	Japan

3. IUCAF Terms of Reference (Revised 2015)

A revision to the statement of IUCAF's composition, operating practices, and Terms of Reference (TOR) – originally dating to 1972, when IUCAF was the Inter-Union Committee on Allocation of Frequencies – was approved by ICSU's Executive Board in 2015 (see http://www.iucaf.org/IUCAF_Terms_Of_Reference.pdf).

4. International and Regional Spectrum Management Meetings Attended by IUCAF Members During 2019

During the period January-December 2019, IUCAF members participated in the international meetings shown in Table 2.

Table 2. International meetings participated in by IUCAF members in 2019.

February	ITU-R CPM-2	Geneva
March	URSI AP-RASC	India
April-May	ITU-R WP 5C	Geneva
May	ITU-R WP 7D	Geneva
May-June	ITU-R WP 1A	Geneva
June	ITU-R WP 4C	Geneva
June	CRAF 62nd meeting	Jodrell Bank, UK
September	RFI2019	Toulouse
October-November	WRC-19	Sharm El-Sheik

Figure 1. The exceptionally-popular IUCAF-branded fidget-spinner.

Additionally, IUCAF members participated in numerous national and regional spectrum-management proceedings, working in their capacities as spectrum managers at their observatories.

5. IUCAF Business Meetings

IUCAF held in-person business meetings during the ITU-R sessions of Working Party 7D in Geneva listed in Table 2, at CPM-2 and WRC-19. During the year, IUCAF business was undertaken via e-mail as matters arose.

6. Finances

The IUCAF budget is held at and managed by URSI. Sustaining financial contributions of €5,000, €2,000, and €1,000 were gratefully received from IAU, URSI, and COSPAR, respectively, for calendar year 2019. Annual expenses of €6000 were incurred in support of travel to the URSI AP-RASC meeting in India in March by former IUCAF member Tomas Gergely, and attendance at WRC-19 by IUCAF member van Driel.

IUCAF continued to distribute its exceptionally-popular IUCAF-branded fidget-spinner (Figure 1).

7. The IUCAF Role in Protecting Passive Radio Science

IUCAF is a global forum where spectrum management concerns of passive radio science in all ITU-R Regions are regularly addressed in a comprehensive manner. The group is expert in the underlying science, in the spectrum-management needs of the science, and in the workings of the spectrum regulatory regime that allocates spectrum and makes the rules for spectrum use. IUCAF has been an important supporter of radio astronomy and passive radio science at the ITU-R in Geneva since its inception in 1960, when the first spectrum band was dedicated to passive research, absent any allocation to active services. The practice of reserving narrow portions of the radio-frequency spectrum for passive radio science subsequently expanded to the point where such bands now provide crucial access to spectrum used by remote sensing to improve weather prediction and quantify the effects of global warming. IUCAF also provides the spectrum-management interface between the radio-astronomy and space-science communities through its work at ITU-R and the Space Frequency Coordination Group. On these accounts IUCAF is a unique resource, with a lengthy record of contributions, the early history of which was recounted by a former IUCAF Chair in "Frequency Allocation: The First Forty Years," by Brian Robinson, *Annual Reviews of Astronomy and Astrophysics*, **37**, 1999, pp 65-96, available at https://tinyurl.com/y5vsgb6x.

IUCAF will celebrate its 60th birthday in 2020. Several IUCAF members are even older.

8. Contact with ICS, the IUCAF Sponsoring Unions IAU, URSI, and COSPAR, and Other International Organizations

IUCAF maintains regular contact with its adhering Unions and the parent body, ISC. These organizations play a strong supporting role for IUCAF, the members of which are thereby greatly encouraged.

IUCAF participated in preparation of a proposal by the IAU Inter-Division Commission C.B4 on Protection of Existing and Potential Observatory Sites for a Focus Meeting on Dark and Quiet Skies and Astronomical Site Protection at the August 2021 IAU General Assembly to be held in Busan, Korea.

9. Outreach

IUCAF's main outreach activities beyond the ITU-R are related to the international spectrum-management schools it has organized at since 2000. At the time of writing, the last such school was held in 2014 in Santiago de Chile, and the next will be held in Stellenbosch, South Africa, March 2-6, 2020. Presentations from the IUCAF schools are available on the IUCAF Web site at http://www.iucaf.org, where some basic information on the organization is reported. IUCAF maintains the World Map of Radio Astronomy Sites and Radio Quiet Zones that has been viewed 54,000 times since its inception in 2008: see http://tinyurl.com/yrvszk.

[25]	Proposed modification to the draft CPM text Chapter 5 - Agenda items 1.8 (Issue B), 1.9.1, 1.9.2	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science	2019-01-28
[24]	Proposed modifications to the draft CPM text Chapter 4 - Agenda item 1.7	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science	2019-01-28
[23]	Proposed modifications to the draft CPM text Chapter 3 - Agenda items 1.6 and 9.1.9	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science	2019-01-28
[22]	Proposed modifications to the draft CPM text Chapter 2 - Agenda item 1.13	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science	2019-01-28
[21]	Proposed modifications to the draft CPM text Chapter 1 - Agenda items 1.11, 1.14 and 1.15	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science	2019-01-28
[20]	IUCAF views on WRC-19 agenda items of concern to Radio Astronomy	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science	2019-01-28

Figure 2. The documents submitted by ICUAF at CPM-2.

10. IUCAF Activities and Concerns in 2019

Most of IUCAF's work during the previous triennium, 2015-2018, was preparation for the 2019 February ITU-R 2nd Conference Preparatory Meeting (CPM-2) of WRC-19, and WRC-19. WRC-19 was held October 28 - November 22 in Sharm El-Sheikh, and was attended by five IUCAF members for periods ranging from 10 days to four weeks. IUCAF strove to acquire a thorough knowledge of the WRC-19 agenda by participating in the spectrum-sharing and compatibility studies conducted in ITU-R Study Groups 1, 4, 5, and 7, and by participating in the treaty text drafting sessions in those Groups. This effort culminated in the January 2020 submission of five CPM-2 input documents, describing suggested modifications of the draft WRC-19 treaty text, and another document summarizing IUCAF's views of methods proposed to satisfy relevant items on the WRC-19 agenda (Figure 2).

The most consequential items in this work package were adopted into the final report of the CPM to WRC-19, especially for Agenda Item 1.14 concerning High Altitude Platform Systems (HAPS), where the unmodified CPM text would not have protected radio-astronomy sites registered after May 2020. Radio-astronomy bands at 153 MHz and 322 MHz received additional protection, including in the latter case from the harmonics of emissions around 160 MHz, an unusual recognition of this kind of spurious emission. These IUCAF positions were incorporated at WRC-19, and a sly modification of footnote 5.208A eventually resulted in a direct reference in the Radio Regulations to ITU-R Recommendation RA.769 containing the basic radio-astronomy service protection thresholds. WRC-19 also saw an acceptable outcome for Agenda Item 1.15 concerning Land Mobile and Fixed Service use of the spectrum at 275 GHz to 450 GHz.

Other Agenda Items did not have such felicitous outcomes. The Iridium satellite system's downlink was granted a primary Maritime Mobile Satellite Service allocation status at 1621 MHz to 1626.5 MHz, which, along with other rule changes, allowed Iridium's entrance as a safety-of-life service in the Global Maritime Disaster and Safety System (GMDSS). Immediately following WRC-19, the Iridium operator renounced its halting attempts to protect the radio astronomy band at 1610.6 MHz to 1613.8 MHz in its new constellation, thereby ensuring a new round of radio-astronomy complaints against this system.

Agenda Item 1.13 saw the adoption of overly-permissive limits on the unwanted emissions of 5G equipment into the passive service band at 23.6 GHz to 24.0 GHz that is used for weather forecasting and other remote-sensing observations of climate change. AI 1.6 allowed non-GSO use of V-band (37 GHz to 42 GHz) spectrum formerly used only by GSO systems, without adequate consideration of the possible harmful effects of modern non-GSO systems on radio-astronomy operations in the frequency band 42.5 GHz to 43.5 GHz.

Much of the work for the WRC-19 cycle actually continued well into 2019, as evidenced by the roster of ITU-R Working Party meetings attended by IUCAF last year. Although interference is usually regarded as a failure of spectrum management, it does occur, and IUCAF was much in evidence at the RFI2019 meeting in Toulouse in September.

Scientific access to radio spectrum was eroded in 2019 in several ways. The potential for harmful interference to allocated spectrum increased when overly-permissive levels of unwanted emissions were allowed for 5G and other devices operating in adjacent and nearby spectrum bands. Frequencies that were formerly used only by fixed point-point links on the ground were increasingly projected to find use by mobile and airborne transmitters, making their signals difficult to avoid even inside radio-quiet and coordination zones. Non-GSO FSS constellations began launching constellations of thousands of satellites, where previously the largest system operated only 66. Broad swaths of clean spectrum for leading-edge research became increasingly hard to find and were increasingly likely to exist in proximity to radio communication signals at levels 60 dB to 100 dB higher than those needed for research. New modes of observing, data-handling, and RFI mitigation will have to be developed if radio astronomy and remote sensing are to operate in such a spectrum environment.

Closer to home, succession planning and matters of engagement were of concern. Nations with major investments in radio astronomy and strong histories of participation are not currently represented by astronomers in national and international spectrum management. IUCAF reached out to astronomers in Thailand, where radio astronomy is newly developing, and encouraged astronomers in some other administrations to re-engage given the occasionally aggressive and unhelpful tactics of their administrations in ITU-R deliberations.

11. Acknowledgements

IUCAF is grateful for the organizational and financial support that has been given by ICS, IAU, URSI, and COSPAR over the past 60 years, especially the URSI Secretariat. IUCAF also recognizes the support given by radio-astronomy observatories, universities, and national funding agencies to individual members, allowing them to participate in the vital work of this committee.

Respectfully submitted,

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IUCAF Web site: http://www.iucaf.org

Announcing WALDO: Massive Public Repository of ELF/VLF Radio Data

We enthusiastically announce a massive online repository of ELF/VLF/LF radio data collected over decades at sites all over the world. As recently written up in EOS (https://eos.org/science-updates/returning-lightning-data-to-the-cloud), the database is known as the World Archive of Low-frequency Data Observations, WALDO, and can be accessed at http://waldo.world.

These data already include or will include many valuable recordings, amongst them

- Antarctic recordings at Palmer Station and South Pole over decades
- Siple Station Antarctica experiment recordings from 1974-1986
- Alaska VLF recordings in conjunction with HAARP experiments
- VLF/LF Data from the 2017 Great American Solar Eclipse
- Narrowband data from global IHY/ISWI/AWESOME receivers
- VLF recordings preceding the 2011 Tohoku M9.0 earthquake

Our hope is for the broader community to think of new ways to analyze these observations that have not been previously considered.

The raw data are in a common format and available for direct download, along with quick-look plots. WALDO includes detailed data descriptions and some available scripts (*MATLAB*, with *Python* coming soon) to view and analyze the data.

WALDO is jointly managed by Georgia Tech (Morris Cohen) and University of Colorado Denver (Mark Golkowski). Currently, there are nearly 200 TB of data, with many hundreds more TBs awaiting upload in the coming weeks and months. In the near term, we are focusing on uploading data previously collected by Stanford University's VLF group (stored on tens of thousands of DVDs), but will also be augmenting it with more recent data collected by CU-Denver and GaTech's receiver networks. If there is a specific dataset you know was recorded that is not yet up at WALDO that you would like to see, please contact us. We can let you know if it still exists, and/or prioritize it if you have a specific interest.

We encourage anyone interested in ELF/VLF and wanting to work with observations to use the data. We are happy to answer any questions about the data as well, or are interested in any feedback on how the WALDO portal is working.

We also welcome anyone else collecting ELF/VLF data who would like to join WALDO and contribute their data as an official partner. Please contact Morris Cohen (mcohen@gatech.edu) and Mark Golkowski (mark.golkowski@ucdenver.edu).

THE CONFERENCE

EuCAP is Europe's largest and most significant antennas and propagation conference attracting more than 1400 participants from academia and industry, and more than 50 industrial exhibitors, from all over the world. It is a great forum for exchange of new technical-scientific achievements, for demonstrating state-of-the-art technology, and for establishing and strengthening professional networks.

The 2021 host country Germany has a strong antennas and propagation community both in academia and industry. Moreover, antennas and propagation play a central role in the current transition of Germany's strong automotive industry towards digitally connected cars and autonomous driving. Finally, many cellular operators and telecommunications equipment vendors have large branches and even headquarters in the host city Düsseldorf and the Rhine-Ruhr-Area, leading the development of 5G. Therefore, EuCAP 2021 will be a unique place to strengthen the link between the scientific antennas and propagation community and the automotive as well as the 5G industry.

INFORMATION FOR AUTHORS

Authors are invited to submit papers online with a minimum length of two and a maximum length of five A4 pages. The paper must contain enough information for the Technical Programme Committee and reviewers to assess the quality of the work in a single acceptance/ rejection review process. It will be possible to revise accepted papers in line with the reviewers' comments.

Submit your paper online at www.eucap2021.org no later than 16 October 2020. The submission requires an EDAS® account, which is free.

Presented papers will be included in IEEE Xplore, if the authors choose this option during the submission process. Compliance to the IEEE format is mandatory in this case.

IET AND EuMA

Authors can apply for publication in a special issue of either Microwaves, Antennas & Propagation (IET) or International Journal of Microwave and Wireless Technologies (EuMA) during the submission process.

IMPORTANT DATES

Deadline	16 October 2020
Notification	22 December 2020
Revised paper	5 February 2021

FIRM DEADLINE

For EuCAP 2021, there will be no extension of the paper submission deadline; late or updated submissions will not be accommodated after the deadline.

www.eucap2021.org

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URSI Conference Calendar

A detailed list of meetings is available on the URSI website at http://www.ursi.org/events.php

December 2019

URSI Benelux Forum 2019
28th annual meeting of the Belgian and Dutch URSI committees
Brussels, Belgium, 3 December 2019
Contact: Prof. P. Van Daele, E-mail: peter.vandaele@ugent.be , http://www.cvent.com/d/fhqlr4

ICMO 2019
International Conference on Meteorological Observations
Chengdu, China, 28 - 31 December 2019
Contact: icmo@cuit.edu.cn
http://icmo2019.cuit.edu.cn/

February 2020

COSPAR ISWAT Inaugural Working Meeting
Port Canaveral, Florida, USA, 10-14 February 2020
Contact: COSPAR Secretariat, 2 place Maurice Quentin, 75039 Paris Cedex 01, France, Fax: +33 1 44 76 74 37, E-mail: cospar@cosparhq.cnes.fr
https://www.iswat-cospar.org/wm2020

URSI - RCRS 2020
2020 URSI Regional Conference on Radio Science
Varanasi, India, 12 - 14 February 2020
Contact: Dr. Somak Bhattacharyya, Convener, RCRS 2020, E-mail: ursi-rcrs2020@itbhu.ac.in
https://conferences.iitbhu.ac.in/URSI-RCRS2020/

March 2020

URSI-France Workshop : Future Networks: 5G and beyond
Palaiseau, France, 11-13 March 2020
Contact: Prof. Alain Sibille, Telecom Paris, E-mail : alain.sibille@telecom-paris.fr
http://ursi-france.telecom-paristech.fr/evenements/journees-scientifiques/2020/2020-en.html

The 2020 e-Workshop on Instrumentation and Calibration in Radio Astronomy
will be held "virtually" on 26 March 2020
This will be an e-Workshop hosted at two sites (Stellenbosch, South Africa and Eindhoven, Netherlands), connected via video link. The aim of the workshop is to have a cost-effective way to give students the opportunity to present their work and make connections with an international audience.
Contact: Dr. Jacki Gilmore, E-mail : ackivdm@sun.ac.za

July 2020

2020 APS-URSI
2020 IEEE AP-S Symposium on Antennas and Propagation and CNC/USNC-URSI joint meeting
will be held "virtually" on 5-10 July 2020
Contact: General Chair: Ahmed Kishk, E-mail: ahmed.kishk@concordia.ca; General Co-Chairs: Lot Shafai, lot.shafai@umanitoba.ca , David G. Michelson, davem@ece.ubc.ca , Yahia M. M. Antar, antar-y@rmc.ca
https://2020apsursi.org/

August 2020

ICEAA - IEEE APWC 2020
The twenty-second edition of the International Conference on Electromagnetics in Advanced Applications
Honolulu, Hawaii, USA, originally 10-14 August 2020, is being postponed
Contact: Mrs. Manuela Trinchero SELENE Srl - Eventi e Congressi, Via Medici 23 10143 Torino, Italy, Tel: +39-011-7499601, Fax: +39-011-7499576, E-mail: iceaa@seleneweb.com or iceaa20@iceaa.polito.it ; Scientific Secretariat: Prof. Guido Lombardi, Politecnico di Torino, E-mail: iceaa20@iceaa-offshore.org
https://www.iceaa-offshore.org/j3

September 2020

NRSC2020 - 37th National Radio Science Conference
Annual meeting of the Egyptian URSI Committee
Cairo, Egypt, 8 - 10 September 2020
Contact: Prof. Rowayda A. Sadek, Secretary, URSI- Egypt National Radio Science Committee, Faculty of Computers and Information Technology, Helwan University, Helwan, Egypt, E-mail: Rowayda_sadek@yahoo.com , Rowayda_sadek@fci.helwan.edu.eg
https://nrsc2020.guc.edu.eg

Kleinheubacher Tagung 2020
Annual meeting German URSI committee
Miltenberg, Germany, 28 - 30 September 2020
Contact: Prof. Dr. Madhu Chandra, Chair of High-Frequency Engineering and Electromagnetic Theory, Faculty of Electrical Engineering and Information Technology, Chemnitz University of Technology, E-Mail: kht2020@etit.tu-chemnitz.de, http://www.kh2020.de

Metamaterials 2020
Fourteenth International Congress on Artificial Materials for Novel Wave Phenomena
New York, NY, USA, 28 September – 3 October 2020 (in an online format)
Contact : E-mail: contact@metamorphose-vi.org
https://congress.metamorphose-vi.org/index.php/8-general-information/1-metamaterials-20161

November 2020

9th VERSIM workshop
Kyoto, Japan, 21-25 November 2020
Contact: Prof. Y. Omura, http://pcwave.rish.kyoto-u.ac.jp/versim/

December 2020

ECOC 2020
European Conference on Optical Communications
Brussels, Belgium, 6-10 December 2020
Contact: Prof. P. Van Daele, E-mail: E-mail: info@ecoc2020.org,
https://ecoco2020.org/

January 2021

EuMW 2020
European Microwave Week 2020
Utrecht, the Netherlands, 10-15 January 2021
Contact: E-mail: headquarters@eumwa.org, https://www.eumweek.com/

COSPAR 2021
43rd Scientific Assembly of the Committee on Space Research (COSPAR) and Associated Events
Sydney, Australia, 28 January – 4 February 2021
Contact : COSPAR Secretariat, 2 place Maurice Quentin, 75039 Paris Cedex 01, France, Tel: +33 1 44 76 75 10, Fax: +33 1 44 76 74 37, E-mail: cospar@cosparhq.cnes.fr
http://www.cospar2021.org

August 2021

URSI GASS 2021
Rome, Italy, 7-14 August 2021
Contact: URSI Secretariat, Ghent University – INTEC, Technologiepark-Zwijnaarde 126, B-9052 Gent, Belgium, E-mail gass@ursi.org
http://www.ursi2020.org/

October 2021

ISAP 2021
International Symposium on Antennas and Propagation
Taipei, Taiwan, 19-22 October 2021
Contact : http://www.isap2021.org/

May 2022

AT-RASC 2022
Third URSI Atlantic Radio Science Conference
Gran Canaria, Spain, 30 May - 4 June 2022
Contact: Prof. Peter Van Daele, URSI Secretariat, Ghent University – INTEC, Technologiepark-Zwijnaarde 126, B-9052 Gent, Belgium, E-mail: peter.vandaele@ugent.be
http://www.at-rasc.com

August 2022

AP-RASC 2022
Asia-Pacific Radio Science Conference 2022
Sydney, Australia, 21-25 August 2022
Contact: URSI Secretariat, Ghent University – INTEC, Technologiepark-Zwijnaarde 126, B-9052 Gent, Belgium, E-mail: info@ursi.org

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