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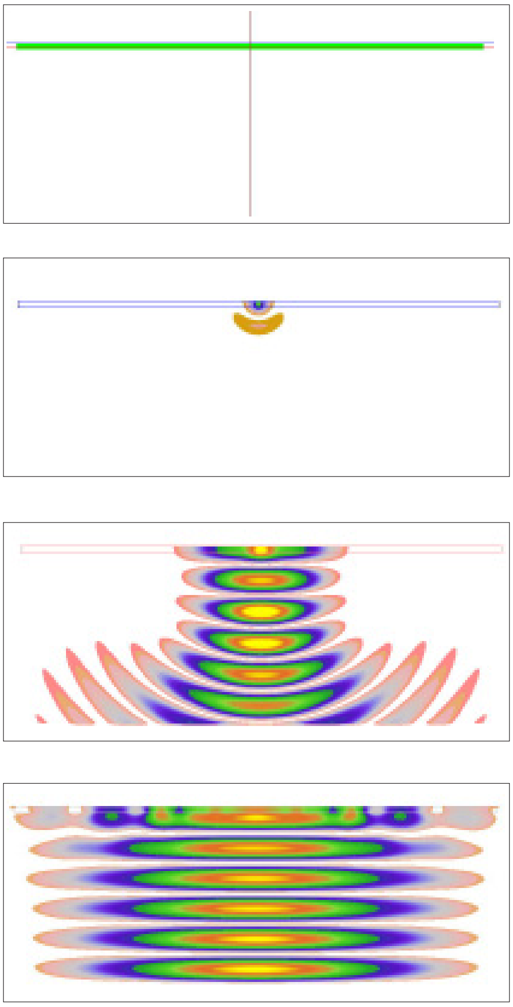

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Contents

Front cover: The electric field intensity radiated by a line source centered in a $\lambda_0/10$ *thick zero-index slab that was terminated in a PMC sheet. See the paper by Engheta et al. on pp. 6-19.*

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Editorial

We have three *Reviews of Radio Science* in this issue, Jim Lin's column, a new column, and calls for papers for several important meetings. A more-detailed first announcement for the 2008 URSI General Assembly also appears in this issue.

A New Column

We have what I hope will become an exciting addition to the *Radio Science Bulletin* beginning with this issue. Peter Watson has joined the *Bulletin* as Associate Editor for Abstracts. He will be editing a column that will publish selected abstracts of doctoral dissertations in radio science. Hopefully, this will serve at least three purposes. First, it should be a useful way of disseminating information about new research in radio science. Second, it will make new PhDs aware of URSI and the *Radio Science Bulletin*, and will hopefully encourage them to become involved in URSI. Third, it will provide a way for the URSI community to become aware of new PhDs in radio science, and that could lead to some good collaborations. If you have completed a PhD in the past year, or if you will be completing one soon, please send the abstract to Peter. If you have been or currently are an advisor to such work, please encourage your student (or new PhD) to send in their abstract. A call for such abstracts, along with an introduction of Peter, appears in this issue.

Our Papers

Metamaterials are manmade materials with engineered electromagnetic properties. Specifically, it is possible to create materials that have negative permittivity, negative permeability, or both, as well as materials that have quite low permeabilities and permittivities. This results in some unusual, fascinating, and potentially very useful effects. In their invited Commission B *Review*, A. Alù, N. Engheta, A. Erentok, and R. W. Ziolkowski first discuss the characteristics of such materials. They then go on to describe a number of applications of such materials. Such materials make it possible to design resonators and waveguides that have at least one dimension that is much smaller than a wavelength. Applications involving anomalous tunneling and transparency are described. Such metamaterials permit designing scatterers that are small compared to a wavelength but still have strong, resonant scattering. The potential of electrically small antennas (e.g., operating at 300 MHz with a maximum dimension of the order of 1%-2% of a wavelength) surrounded by metamaterial enclosures and having very high radiation efficiencies is demonstrated with several examples. The enhancement of transmission through very small apertures using metamaterials is also discussed. This review does a very nice job of introducing this fascinating new area of electromagnetics.

Computational electromagnetic methods, such as the Finite-Difference and Finite-Element methods, have become common tools for many scientists and engineers. In their invited Commission B *Review*, Rolf Schuhmann and Thomas Weiland show that the Finite Integration Technique can provide a common basis for analyzing all of these methods. They begin by presenting an easily understood theory for discretizing Maxwell's equations. They show how geometric discretization leads to the Finite Integration Technique, while discretizing differential operators leads to the Finite-Difference method, and discretization of functional spaces leads to the Finite-Element method. The relationships among all of these approaches are examined in some detail. The use of these techniques for conformal modeling in computational electromagnetics is then reviewed. A number of recent results in this area are reported, and some open questions are discussed. Part of the value of this *Review* is the understanding it brings of the fundamentals underlying these commonly used computational tools.

William Amatucci has provided us with one of the most comprehensive *Reviews* we have had in a long time. The topic is the use of laboratory experiments to model and understand space plasmas. This invited Commission H *Review* provides an extensive overview of space plasmas, written in a manner such that a background in plasma physics isn't necessary to understand the material. It provides a very easy-to-read introduction to the environments in both the laboratory and in the Earth's ionosphere and nearby space. The variety of available devices for simulating and experimenting with plasmas similar to those found in the geospace regions is described. After reviewing waves found in the neutral atmosphere, a discussion of waves associated with plasmas follows: Langmuir waves, ion acoustic waves, Alfvén waves, ion cyclotron waves, and whistler and lower hybrid waves. The various ways in which magnetic field lines influence and are influenced by plasma waves are then explained, along with the laboratory experiments that have been done to investigate them. The *Review* finishes with a discussion of issues for future laboratory experiments. The list of references provided is extensive, and will hopefully prove very useful to anyone who wishes to learn more about any of the topics covered.

Our thanks to Lot Shafai of Commission B, Karl Langenberg of Commission B, and Yoshiharu Omura of Commission H for providing these *Reviews*. Of course, we also thank Phil Wilkinson for his significant efforts in coordinating the *Reviews*.

Jim Lin's column on Radio-Frequency Radiation Safety and Health looks at current research activities in the area of bioelectromagnetics in Europe. As he points out, there are some important opportunities in a major European initiative.

Please consider submitting a paper to the *Radio Science Bulletin*. We are fully peer-reviewed, fully abstracted and indexed by INSPEC, and reach the broadest audience of radio scientists. If you have a paper that is of interest across the fields of interests of two or more URSI Commissions, then please send it to me.

This issue will hopefully reach you either right at the end of the old year, or just at the beginning of the new year. May the new year bring you health, happiness, peace, prosperity, and interesting radio science!

Ross

Radio Science Doctoral Abstracts

Call for Submissions

In order to encourage dialogue with young radio scientists, we propose to publish the abstracts of relevant doctoral dissertations or theses in the fields of radio science as soon as they are approved by universities or other degree awarding institutions.

We thus call upon supervisors or research group leaders to bring this opportunity to the attention of recently qualified doctoral graduates, asking them to e-mail their abstracts to the address given below. The date of publication should be given, with full details of the address of the awarding institution and also an e-mail address for the author. It would also be helpful to indicate which URSI Commissions relate most closely to the doctoral work.

To start the ball rolling, doctoral supervisors might like to go back through the last academic year for suitable candidate doctoral dissertations.

Peter Watson
University of Bath
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Introducing Peter Watson, Associate Editor for Abstracts

Prof. Watson was formerly Head of the Department of Electronic and Electrical Engineering at the University of Bath, and is currently Professor Emeritus. He is a Fellow of the Institution of Electrical Engineers, and has chaired several international conferences on behalf of the IEE and the International Union of Radio Science (URSI). He is a former Chair of the IEE Professional Group on Antennas and Propagation, and was until recently the Chair of the UK URSI National Committee. His research activities cover radio propagation, radio remote sensing, and radio communications.

Prof. Watson took his first degree and PhD at the University of Durham. His career spanned 12 years in industry (with British Telecom, the European Space Agency, and BIT Ltd.), in addition to his time as an academic with the Universities of Bath, York, and Bradford.

XXIX General Assembly of the International Union of Radio Science
Union Radio Scientifique Internationale

August 07-16, 2008
Hyatt Regency Chicago Hotel on the Riverwalk
151 East Wacker Drive, Chicago, Illinois 60601, USA

First Announcement

The XXIX General Assembly of the International Union of Radio Science (Union Radio Scientifique Internationale: URSI) will be held at the Hyatt Regency Chicago Hotel in downtown Chicago, Illinois, USA, August 07-16, 2008.

The General Assemblies of URSI are held at intervals of three years to review current research trends, present new discoveries and make plans for future research and special projects in all areas of radio science, especially where international cooperation is desirable. The first Assembly was held in Brussels, Belgium, in 1922, and the latest in New Delhi, India, in 2005. Assemblies were held in the USA on three previous occasions: in Washington, DC, in 1927 and 1981, and in Boulder, Colorado, in 1957.

The XXIX General Assembly will have a scientific program organized around the ten Commissions of URSI and consisting of plenary lectures, public lectures, tutorials, invited and contributed papers. In addition, there will be workshops, short courses, special programs for young scientists and graduate students, and programs for accompanying persons. More than 1,500 scientists from more than fifty countries are expected to participate in the Assembly.

The Call for Papers will be issued in mid-2007, will be published in the *Radio Science Bulletin* and in the *IEEE Antennas and Propagation Magazine*, and will be posted on the URSI Web site. It is expected that all contributions should be received by the end of January, 2008, and that authors will be notified of the disposition of their submissions by the end of March, 2008.

http://www.ursi.org

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Single-Negative, Double-Negative, and Low-Index Metamaterials and their Electromagnetic Applications

A. Alù
N. Engheta
A. Erentok
R.W. Ziolkowski

Abstract

Metamaterials, which are engineered media characterized by electromagnetic constitutive parameters with anomalous values, may show counterintuitive properties in their interactions with electromagnetic waves. Here, we review some of the properties and potential applications we have recently presented in the technical literature: properties and applications in which plasmonic materials and metamaterials may be utilized to overcome some conventional physical limits. Resonances arising in electrically small regions of the interface where these materials are paired with common materials are shown to be potentially attractive for this purpose in some electromagnetic problems: for instance, in guiding and radiating structures. The anomalous refractive properties at such "complementary" interfaces and the negative values of polarizability attainable in such materials are also shown to offer potentials for several applications.

1. Introduction

Natural plasmonic materials (noble metals and some dielectrics), which have electric resonances in the microscopic molecular domain that induce an overall negative electric permittivity for the bulk medium at optical frequencies, are known to show an interesting and anomalous electromagnetic response in the visible regime [1]. In a similar way, by mimicking the molecular functions that cause these anomalous resonances, but scaled at lower frequencies, metamaterials with nonstandard values of their constitutive parameters have recently been conceptually proposed and synthesized by properly embedding suitably shaped inclusions in a given host material [2]. Nowadays, advances in simulation and fabrication technologies allow a rather broad flexibility in the design of these metamaterials, and, hence, their electromagnetic responses. The potential ability to engineer the electromagnetic responses of materials for a wide variety of applications has stimulated significant interest in metamaterials. Interestingly enough, the recent advances in nanotechnology and molecular bioengineering are leading researchers to speculate about the possibility of bringing these metamaterial concepts back to the visible frequencies, and about the proper design of artificial molecular shapes to achieve artificial optical metamaterials in order to tailor their electromagnetic properties at infrared and visible frequencies.

If we assume that the material response is isotropic – at least for a given polarization of the fields and in a specific range of frequencies – and that the magneto-electric coupling is negligible, the time-harmonic Maxwell's equations (with an $e^{j\omega t}$ time dependence) in the absence of impressed sources are locally written as

$$\nabla \times \mathbf{E} = -j\omega\mu\,\mathbf{H}\,, \tag{1}$$

$$\nabla \times \mathbf{H} = j\omega\varepsilon\,\mathbf{E}$$

where ε, μ respectively represent the local electric permittivity and magnetic permeability, and are complex quantities when losses are taken into account. From their electromagnetic wave interactions, most of the materials in nature are characterized by these two quantities, yielding values compatible with the constraints $\mathrm{Re}[\varepsilon] \geq \varepsilon_0$,

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A. Erentok and R. W. Ziolkowski are with the University of Arizona, Department of Electrical and Computer Engineering, Tucson, Arizona, USA.

This is one of the invited *Reviews of Radio Science* from Commission B.

$\mathrm{Re}[\mu] \geq \mu_0$, $\mathrm{Im}[\varepsilon] < 0$, $\mathrm{Im}[\mu] < 0$, which imply the passive nature of the material and an index of refraction greater than or equal to the free-space value. In principle however, at a given frequency the real parts of the permittivity and permeability of a passive material may yield any real value, provided a suitable temporal dispersion satisfies the constraints dictated by causality (i.e., the Kramers-Krönig relations [3]). Materials with the simple constitutive relations described by Equation (1) may be categorized according to the diagram of Figure 1: if both the permittivity and permeability have positive real parts, as most of the materials in nature do, they may be called "double-positive (DPS)" media, whereas if both of these quantities are negative, as in the third quadrant of Figure 1, the corresponding materials may be called "double-negative (DNG)" [4]. Owing to their anomalous wave refraction, such materials have been the subject of great interest in the engineering and physics communities, particularly since their experimental realization by the UCSD group in 2000 [2]. Media with a negative real part of the permittivity but a positive permeability are located in the second quadrant, and are named "ε-negative (ENG)." They include plasma and plasmonic materials (noble metals and some polar dielectrics) below their plasma frequencies. Applications of plasmas and other forms of ε-negative materials in several different fields have been studied for decades. Recently, due to the development in nanotechnologies, there has been a renewed interest in the plasmonic resonances associated with sub-wavelength particles and interfaces. In the fourth quadrant, we have the μ-negative (MNG) materials, which may be realized with ferromagnetic materials, or synthesized with suitable inclusions in a host material [5]. The artificially-realized μ-negative materials are essential, basic constituents in the construction of double-negative materials. In analogy with double-negative materials, ε-negative and μ-negative materials may be collectively named "single-negative (SNG)" media. Near the two axes of Figure 1, where the real part of one of the constitutive parameters is near zero, the materials may be termed ε-near-zero (ENZ) and μ-near-zero (MNZ) materials, depending on the constitutive parameter that yields anomalous values. Materials with both constitutive parameters equal to zero, which fall at the origin of Figure 1, have been termed zero-index materials [6]. We note that the realization of single-negative materials may be relatively easier than that of double-negative materials, and therefore particular efforts have recently been aimed at exploring how some of the exciting phenomena and applications predicted and studied in double-negative materials can be transferred into single-negative media.

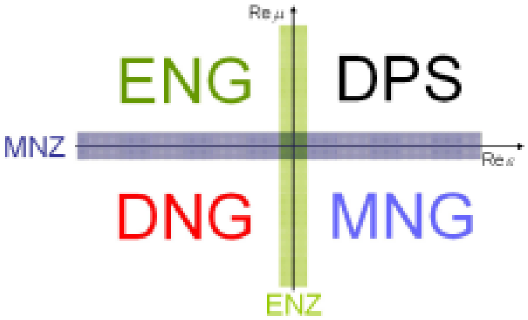

Figure 1. The nomenclature of metamaterials, based on the values of the real parts of their permittivity and permeability.

As underlined above, low or negative values of the effective constitutive parameters may be properly tailored at specific frequencies, but they are associated with dispersive media [7]. In passive materials, the frequency dispersion must also obey some specific constraints that are related to the causality and energy relations. In particular, in the low-loss scenario, even though ε, μ may both be negative quantities, their frequency behavior should satisfy the following conditions:

$$\frac{\partial(\omega\varepsilon)}{\partial\omega} \geq 0, \tag{2}$$

$$\frac{\partial(\omega\mu)}{\partial\omega} \geq 0.$$

This implies that the total electromagnetic energy in the material must be positive. In the following, we review some of the potential applications of metamaterials, recently proposed and reported in the literature. Our analysis of these different problems takes into account the possible dispersion and loss characteristics of the metamaterials; the associated detrimental effects are reduced by properly choosing the operating frequencies in regions in which their influence may be less drastic.

2. Applications of Negative Materials

2.1 Sub-Wavelength Cavities, Resonators, and Waveguides

The double-positive and double-negative materials support monochromatic plane-wave propagation in the form $e^{j(\omega t - kz)}$, since their wave vector, $k = \omega\sqrt{\varepsilon}\sqrt{\mu}$, is a real number in the limit of no losses. In particular, the wave vector and Poynting vectors are parallel in a double-positive material, whereas in a double-negative material they are oppositely directed, implying backward-wave phase propagation and negative phase velocity for a wave carrying power in the positive direction. On the other hand, the ε-negative and μ-negative materials are opaque to radiation, since they support only evanescent waves, i.e., k is imaginary. As was stated in [8], when employed by themselves, even the most awkward negative materials do not show particularly appealing properties: "The unconventional electromagnetic characteristics of metamaterials are exhibited when these materials are paired with other materials with at least one oppositely-signed constitutive parameter" [8]. In fact, the anomalies in employing materials with negative constitutive parameters arise at the interface between two media with at least one pair of oppositely signed parameters. This can play a major role in the anomalous behavior of the combined structure. In fact, at the boundary between such media, the continuity of the tangential electric and magnetic field components implies

$$\frac{1}{-j\omega\mu_1}\frac{\partial E_{1,tan}}{\partial n}\bigg|_{Interface} = \frac{1}{-j\omega\mu_2}\frac{\partial E_{2,tan}}{\partial n}\bigg|_{Interface},$$

$$\frac{1}{j\omega\varepsilon_1}\frac{\partial H_{1,tan}}{\partial n}\bigg|_{Interface} = \frac{1}{j\omega\varepsilon_2}\frac{\partial H_{2,tan}}{\partial n}\bigg|_{Interface},$$

where $\partial/\partial n$ is the normal derivative with respect to the interface, and ε and μ are the permittivity and permeability in the two media. It is clear that when μ_1 and μ_2, and/or ε_1 and ε_2, have opposite signs, i.e., at the interface between ε-negative, μ-negative double-negative and/or double-positive materials, the derivatives of the tangential fields on both sides of this interface will have opposite signs. This peculiar "V-shaped" discontinuity in the derivative is a symptom of a concentrated resonant phenomenon at this "complementary" interface (similar to the current and voltage distributions at the junction between an inductor and a capacitor at the resonance of a *L-C* circuit).

The possibility of designing thin, sub-wavelength cavity resonators and parallel-plate waveguides, in which a layer of double-negative, ε-negative or μ-negative material is paired with a double-positive layer, or in which ε-negative and μ-negative materials are paired together, has been suggested following these premises [9-12, 13]. This compact resonance, together with the phase-compensation typical of negative materials, in fact allows obtaining resonant modes in electrically thin parallel-plate structures containing such bi-layered fillings. An example is provided in Figure 2, where the electromagnetic fields in a sub-wavelength one-dimensional cavity, closed by perfect electric plates and filled with such a complementary bi-layer stratified along the z direction, are plotted. You can see the V-shaped distribution at the interface that allows a compensation for the electrically small lateral dimension of such a cavity.

Similar structures can also support fast and slow TE and TM guided modes with no cutoff thickness (i.e., zero cutoff thickness), which therefore are independent of their total size. This is in contrast to electrically large waveguides, which will only support one single propagating mode [10]. In the thin-waveguide limit, it is possible to show how – unlike in the usual case – the dispersion relation for the supported modes does not depend on the total size of the waveguide, $d = d_1 + d_2$, but instead on the *ratio* of the two slab thicknesses, d_1/d_2. This property leads to the theoretical possibility of having waveguides supporting a resonant mode even when the total thickness becomes much less than the wavelength. The peculiar flow of energy in such waveguides consists of two anti-parallel flows, one each in the two material slabs. This "incident" and "reflected" behavior happens in any standing-wave phenomenon where there is a discontinuity or an abruption. However, in this peculiar situation, the "incident" and "reflected" power belong to the same forward or backward mode, while flowing in distinctly different regions of space. Further details regarding this counterintuitive phenomenon are given in [13].

This sub-wavelength resonator concept has been used to advance the concept of an ultra-thin laser cavity [12]. The basic geometry is shown in Figure 3a: a metamaterial slab

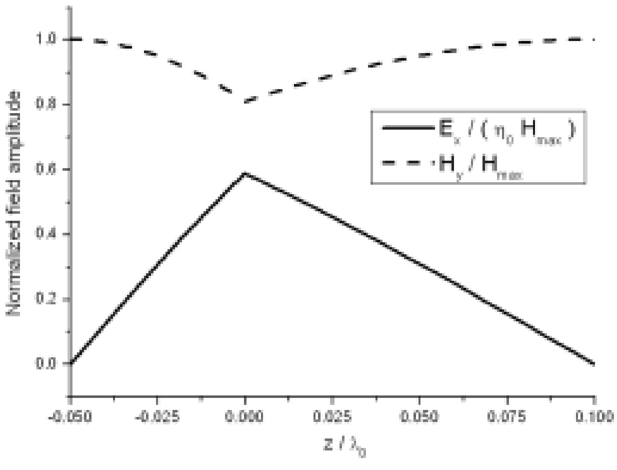

Figure 2. The electric and magnetic field distribution for a one-dimensional sub-wavelength cavity closed by perfectly conducting walls and partially filled with a double-negative metamaterial (the stratification is along the z axis) (from [11], ©2005 The Institute of Electrical and Electronics Engineers).

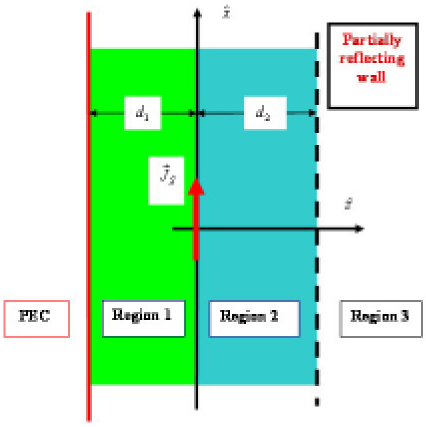

Figure 3a. The geometry of an ultra-thin laser cavity for a double-positive/double-negative and an ε -negative/ μ -negative bi-layer. The source was sandwiched between two metamaterial slabs that were terminated with a PEC and a partially reflecting mirror (from [12], ©2006, Optical Society of America).

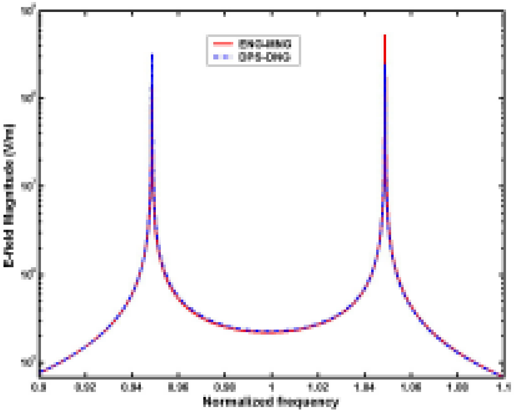

Figure 3b. The output electric field magnitudes of an ultra-thin laser cavity for a double-positive/ double-negative and an ε -negative/ μ -negative bi-layer. The source was sandwiched between two metamaterial slabs that were terminated with a PEC and a partially reflecting mirror (from [12] ©2006, Optical Society of America).

bi-layer is terminated with a perfect electric conductor (PEC) and a partially reflecting mirror (e.g., $|R_M|^2 = 0.98$). For example, the bi-layer could be either a double-positive/ double-negative or an ε -negative/ μ -negative pair, with $|\mu_r| = 1.0$, $|\varepsilon_r| = 0.1$. Despite a length that is only $\lambda_0/10 = 50$ nm in size, this cavity resonates and produces enhanced output fields, as shown in Figure 3b.

Similar sub-wavelength resonant cavities and waveguides may also be envisioned in cylindrical or spherical geometries, both as closed or open structures. The interface between complementary materials may also induce a compact resonance in these sub-wavelength two-dimensional or three-dimensional configurations [14-15]. For instance, open waveguides based on surface-wave propagation along double-negative, ε -negative, or μ -negative planar slabs or cylindrical rods have been shown to support anomalous modes. A standard open dielectric waveguide may support a mode with zero cutoff, but its lateral field distribution is spread out in the space around the slab when the slab section is too small. Consequently, the effective cross section of the guided mode easily becomes much larger than the physical lateral dimension of the slab. On the other hand, when a double-negative slab or rod is considered, highly concentrated guided modes that propagate in the material are still possible, even for very thin double-negative slabs. This leads to the possibility of building ultra-thin open waveguides, overcoming the standard diffraction limitation in energy transport and reducing the cross talk between densely packed waveguides [15].

2.2 Anomalous Tunneling and Sub-Wavelength Focusing

While an isolated ε -negative or μ -negative material is opaque to any incident electromagnetic waves, pairing it with a complementary material (i.e., building an ε -negative/ μ -negative pair) may lead to an anomalous tunneling effect and transparency, induced by the resonance arising at their interface [16]. It can be shown that a suitable choice of the material parameters produces a total tunneling of the interacting fields, i.e., a zero reflection from the pair, which occurs for both the incident propagating and evanescent waves. In this case, the bi-layer would displace a virtual image on the other side of the pair with the sub-wavelength detailed information of the image being mainly restored. In fact, inside such a pair the typical exponential decay of the evanescent waves becomes an “exponential growth,” justified by the multiple reflections that result from the resonant interface. This anomalous behavior clearly overcomes the intrinsic resolution limitations of any standard image displacer [16]. In Figure 4, a schematic of the functionality of this flat bi-layer as an image displacer is depicted.

The anomalous tunneling behavior of these bi-layers has been studied in both the frequency and time domains [17]. For example, a Finite-Difference Time-Domain (FDTD) engine was used to simulate the initial transient response of the system and its convergence towards the steady-state conditions. The conjugate-matched pair had the material parameters

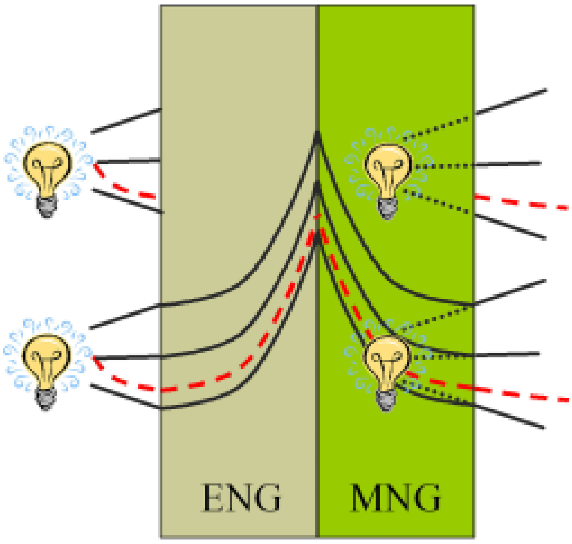

Figure 4. A schematic model of the virtual displacer, made with a complementary ε-negative/μ-negative bi-layer. Propagating and evanescent waves that construct a given object on the entrance face of the bi-layer (represented, respectively, by the black (solid) rays and the red (dashed) exponential curve) are restored as a virtual image on its exit face, including all of their sub-wavelength details.

$$\varepsilon_{ENG}\left(\omega_d\right) = -\varepsilon_{MNG}\left(\omega_d\right) = -3\varepsilon_0 ,$$

$$\mu_{ENG}\left(\omega_d\right) = -\mu_{MNG}\left(\omega_d\right) = 2\mu_0 ,$$

$$d_{ENG} = d_{MNG} = \lambda_0/10 ,$$

with $\lambda_0 = 2\pi/\left(\omega_d\sqrt{\varepsilon_0\mu_0}\right) = 1.0$ cm being the wavelength at the sinusoidal excitation frequency $f_0 = 30$ GHz. Figure 5a shows the electric field distribution throughout the FDTD simulation region at two different, but close, snapshots in time, when steady-state was achieved. The plots clearly show the predicted total tunneling, with the same phase at the entrance and the exit face of the bi-layer. Moreover, it is evident how, at this point in time, the "growing-exponential" distribution was already present at the ε-negative/μ-negative interface. This was consistent with the fact that the wave was evanescent in each of the slabs of the bi-layer, but its amplitude and phase was the same at the entrance and exit faces. The time histories of the electric field at the entrance and exit faces of the bi-layer and at the ε-negative/μ-negative interface are shown in Figure 5b. They demonstrate the fact that a large number of source periods are needed for the anomalous tunneling behavior to express itself and to reach its steady state.

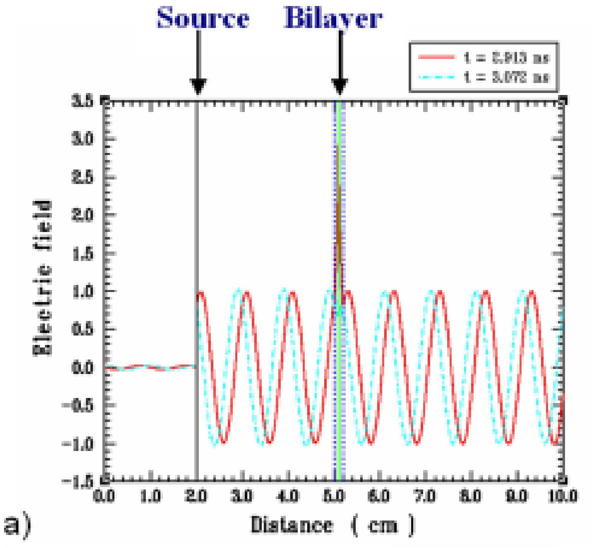

Figure 5a. The predicted anomalous tunneling through a complementarily-matched ε-negative/μ-negative bi-layer was confirmed with one-dimensional FDTD simulations: The electric field distribution at two snapshots in time (from [17], (c)2006, American Physical Society).

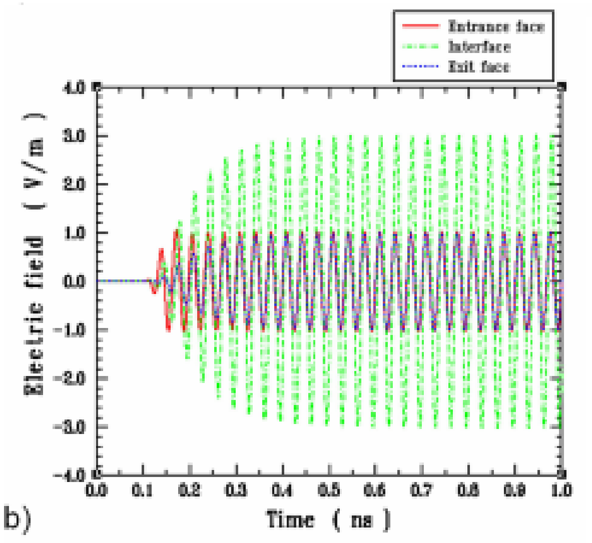

Figure 5b. The predicted anomalous tunneling through a complementarily-matched ε-negative/μ-negative bi-layer was confirmed with one-dimensional FDTD simulations: The electric-field time histories (from [17], (c)2006, American Physical Society).

2.3 Resonant Scattering Properties of Sub-Wavelength Objects

Electrically small objects generally show a weak scattering of any incident radiation, and the scattered fields are strongly dominated by the dipolar component. A peak in the scattering cross section of an object is in fact associated with a polariton resonance of its structure, similar to an open cavity at its resonance frequency. Usually such resonant modes can be excited in large objects, with sizes that are at least comparable with the wavelength, as occurs in any standard cavity. However, by exploiting the anomalous resonance induced by a proper pairing of positive and negative materials, it is also possible to overcome the weak-scattering limits associated with the small scatterer case [18], similar to what was described in the previous section.

Considering coaxial cylindrical shells or concentric core-shell spherical or elliptical systems of complementary materials, a resonant polariton mode may be induced independently of the total size of the object, but rather depending on the filling ratio. The intrinsic possibility of tailoring a large scattering width from electrically small objects is strictly related to the compact resonance that such complementary pairs exhibit. When the corresponding material polariton is at the resonance (caused by the interface resonance when sub-wavelength objects are considered), an anomalously strong scattering is expected from electrically small objects. This can be seen in Figure 6, where different scattering-order coefficients c_n^{TM} (as classically defined, see [18]) are plotted for an example of a double-positive/ε-negative core-shell sub-wavelength sphere as functions of the filling ratio of the two materials. We note how for specific ratios, one of the scattering orders reaches its absolute maximum (which is when $c_n^{TM} = -1$, at a polariton resonance), leading to a resonant total scattering cross section that is given by the standard expression

$$Q_s = \frac{2\pi}{|k_0|^2} \sum_{n=1}^{\infty} (2n+1)\left(\left| c_n^{TE} \right|^2 + \left| c_n^{TM} \right|^2 \right), \qquad (3)$$

where $k_0 = 2\pi/\lambda_0$ is the free-space wavenumber.

It is interesting to remark that in such sub-wavelength resonant systems, one may not only tailor the scattering cross section amplitude to values comparable to those of a much larger object at its resonance, but in principle one may also select the desired scattering pattern. While a small object generally scatters an azimuthally symmetric dipolar field, selected values of the filling ratio in these complementary core-shell systems may allow a different scattering order to dominate, with a more-directive beam [18]. This may have interesting implications in the design of more-directive radiators with a small electric aperture, due to the excitation of higher-order resonant modes, as suggested in [19]. In principle, any order may be excited at resonance, even though the presence of ohmic losses and the narrow frequency bandwidth may eventually limit this possibility.

2.4 Resonant Enhancement of the Power Radiated by Electrically Small Antennas

An electrically small dipole antenna is known to have a large impedance mismatch to any realistic power source, i.e., it has a very small radiation resistance while simultaneously having a very large capacitive reactance. It thus requires a properly designed matching network – usually consisting of a large inductance and a quarter-wavelength transformer – to achieve a high overall radiation efficiency. A different paradigm for achieving matching, i.e., enclosing an electrically small dipole antenna in an electrically small epsilon-negative (ENG) shell, has recently

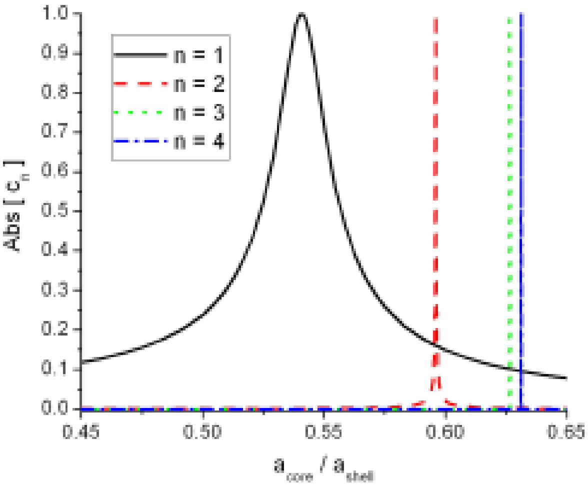

Figure 6. The absolute values of the scattering coefficient, c_n^{TM}, as defined in [18], for a spherical core-shell system with outer radius $a_{shell} = \lambda_0/20$, core permittivity $\varepsilon_{core} = 10\varepsilon_0$, and shell permittivity $\varepsilon_{shell} = -1.2\,\varepsilon_0$, as a function of the filling ratio of the sphere (©2005, American Institute of Physics).

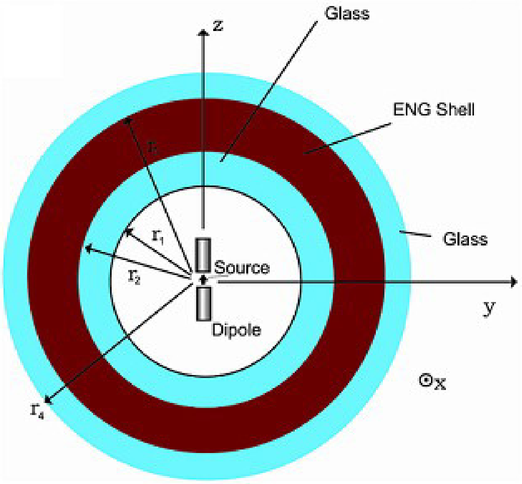

Figure 7. An electric dipole antenna surrounded by a concentric multilayered spherical shell that consists of two glass shells surrounding an ε-negative shell.

been demonstrated [20-25]. The "negative capacitance" (which is equivalent to an inductance) of the ε-negative shell compensates for the capacitive nature of the electrically small dipole antenna, functioning as a distributed matching element that forms this "geometrically" resonant system. It was shown in [21] that this source problem is dual to the scattering problem discussed in the previous section.

The problem of an infinitesimal dipole centered in the five-region (four-nested-sphere) geometry shown in Figure 7 has been solved [23, 24]. Realizing an ε-negative medium with an inclusion-based metamaterial, without using an array of infinite wires at UHF frequencies, is very challenging. However, it is straightforward (in principle) with a plasma. An ε-negative shell modeled as a lossy cold plasma has the relative permittivity

$$\varepsilon_r(\omega)=\frac{\varepsilon(\omega)}{\varepsilon_0}=1-\frac{\omega_p^2}{\omega(\omega-j\Gamma)}, \qquad (4)$$

where ω_p is the plasma frequency, and Γ is the collision frequency of this Drude model. A 10 mm long electric dipole antenna, centered in a single ε-negative spherical shell, was modeled. The inner radius of the ε-negative shell was 10 mm; its outer radius was 11.68 mm. The permittivity of the ε-negative shell was described by the frequency-dependent Drude model, with $\mathrm{Re}\left[\varepsilon_r(\omega_0)\right]=-10$. The relative permittivity was more negative and the shell was thinner than the cases considered in [22-24], in agreement with the basic *LC* resonator description of the electrically small dipole (capacitive element)/ε-negative shell (inductive element) system given in [22]. The radiated power ratio (RPR) (the ratio of the total power radiated by the dipole in the presence of the metamaterial shells and in free space for the same constant driving current, e.g., 1 A) was obtained for various values of the collision frequency: these results are shown in Figure 8a. The magnitude of the real part of the magnetic field associated with the lossless version of this electrically small resonant system is illustrated in Figure 8b.

More realistic electrically small center-fed electric dipole/ε-negative spherical shell and coax-fed electric monopole/ε-negative hemispherical shell antenna systems have also been modeled numerically, using Ansoft's *High Frequency Structure Simulator* (*HFSS*) [22-24]. The input resistance and reactance of these realistic antenna/ε-negative shell systems were obtained from these numerical models. It has been shown in [22-24] that these systems could be designed to have geometrical resonances for which the relative gains were analogous to the radiated power ratios obtained with the analytical models. With

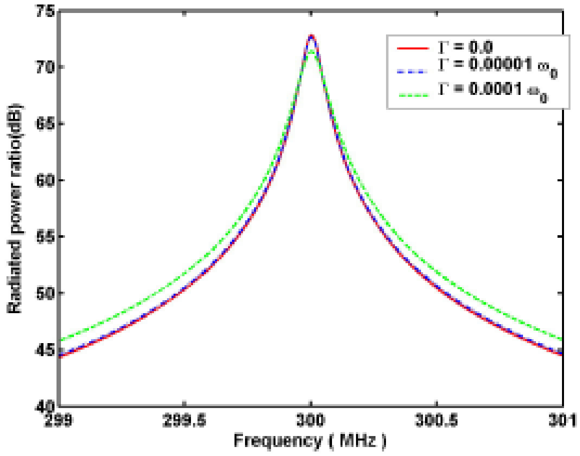

Figure 8a. Enclosing an infinitesimal dipole antenna in a resonant electrically-small single-layer ε-negative shell significantly enhanced the power radiated by the antenna for a given constant driving current: The radiated power ratio, assuming that the permittivity of the shell was described by a Drude model.

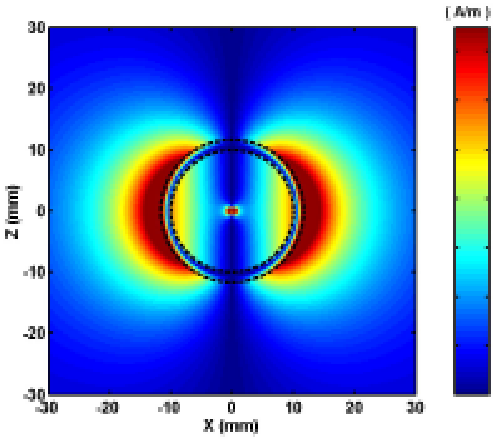

Figure 8b. Enclosing an infinitesimal dipole antenna in a resonant electrically-small single-layer ε-negative shell significantly enhanced the power radiated by the antenna for a given constant driving current: The magnetic field distribution for the lossless case.

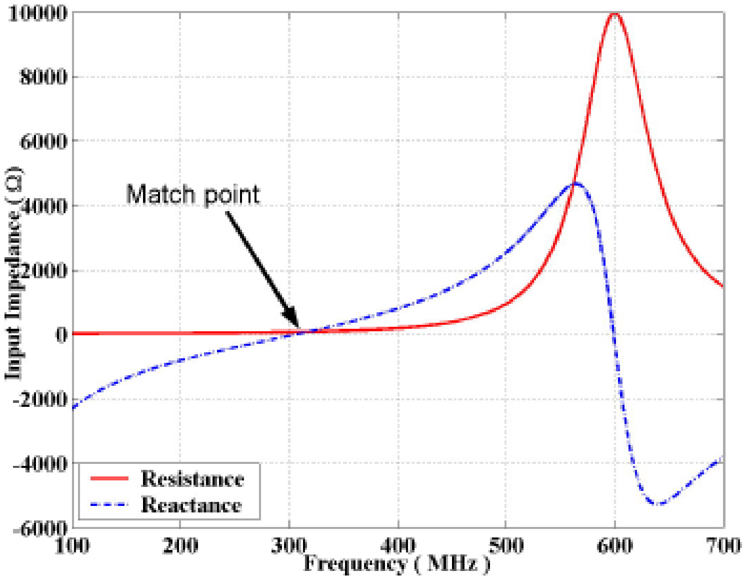

Figure 9. The input impedance predicted by HFSS for a center-fed dipole enclosed in a glass-plasma-glass system fed with a 1 W, 75 Ω source, assuming that the shell's permittivity was frequency independent and that all of the layers were lossless.

further tuning, it has also been shown that an "antenna" resonance – where the system has a zero input reactance and an input resistance that is matched to a specified source resistance – can also be realized to yield a very good impedance match to the source. For example, consider a five-region configuration in which a plasma is enclosed in a glass vessel: i.e., consider a glass vessel with $\varepsilon_r(\omega) = 2.25$, having one wall that is 1 mm thick and an inner radius equal to 8 mm, and a second wall that is also 1 mm thick and an inner radius equal to 11.928 mm, which encloses a center-fed electric dipole with a length of 8.2 mm and a radius of 0.59 mm. For a plasma density of N_e electrons per cm^3, the plasma frequency is $f_p = \omega_p / 2\pi = 8.98\times10^3\sqrt{N_e}$. Setting the collision frequency to zero so that the plasma medium is lossless, $\Gamma = 0.0$, the plasma density required to produce $\mathrm{Re}\left[\varepsilon_r(\omega_0)\right] = -10.0$ at $f_0 = 300$ MHz is $N_{e,res} = 1.229\times10^{+10}\ cm^{-3}$. This plasma density is typical of those densities found in a fluorescent light tube, i.e., on the order of $10^{10} - 10^{11}\ \mathrm{cm}^{-3}$, so that this configuration could be experimentally achieved. The *HFSS*-predicted input resistance and impedance values for a 1 W, 75 Ω source, and for a frequency-independent, lossless, glass/ ε-negative plasma-glass shell system with $\varepsilon_r(\omega_0) = -10.0$, are shown in Figure 9. Values of $Z_{input} = 72.159\ \Omega$ at 307.22 MHz and $Z_{input} = 68.42 - j53.43$ W at 300.00 MHz were found. Thus, for this hypothetically lossless system, the radiated power efficiency was approximately 99.86% at 307.22 MHz, and 87.62% at 300 MHz, for 1 W input power. This was despite the antenna being electrically small, i.e., with the maximum dimension of the antenna system being defined by the outer radius of the ε-negative shell, $a = 12.928$ mm, and the electrical length being $k_0 a = 0.083$. The corresponding coax-fed monopole in the corresponding glass-plasma-glass hemispherical shell system would have essentially the same behavior [22-24]. The monopole-hemispherical glass-plasma-glass geometry may be a more straightforward approach to a proof-of-concept realization of this system.

We recall that the fundamental limits on the radiation quality factor, Q, associated with electrically small antennas have been explored by many authors. The exact form of the minimum of the Q, which we will call here the Chu limit, is known to be

$$Q_{Chu} = \frac{1}{(ka)^3} + \frac{1}{ka} \approx \frac{1}{(ka)^3} \quad \text{for} \quad ka \ll 1, \qquad (4)$$

where a is the radius of the radiansphere (the minimum-radius sphere) surrounding the antenna system. On the other hand, if $f_{+,3dB}$ and $f_{-,3dB}$ represent the frequencies above and below the resonance frequency where the radiated power falls to half its peak value, the fractional bandwidth, FBW, is related to the radiation quality factor, Q_{BW}, by the relation $FBW = \Delta f_{3dB} / f_{0dB} = 1/Q_{BW} \approx (ka)^3$, where $\Delta f_{3dB} = f_{+,3dB} - f_{-,3dB}$. Consequently, as the electrical size of the dipole antenna decreases, the minimum Q value in free space increases dramatically, causing a corresponding decrease in the fractional bandwidth of the antenna. The quality factor and the fractional bandwidth are traditionally thought to approach their Chu limits only if the antenna efficiently utilizes the available volume within the radiansphere. When losses are present, the radiation efficiency, η_{rad}, and the quality factor for the lossy and lossless cases, are related by $Q_{Lossy} = \eta_{rad}\, Q_{Lossless}$, i.e., the fractional bandwidth is increased in the presence of the loss at the cost of radiated power. Thus, the lossless cases are sufficient to bound the fractional bandwidth and quality factors of the system.

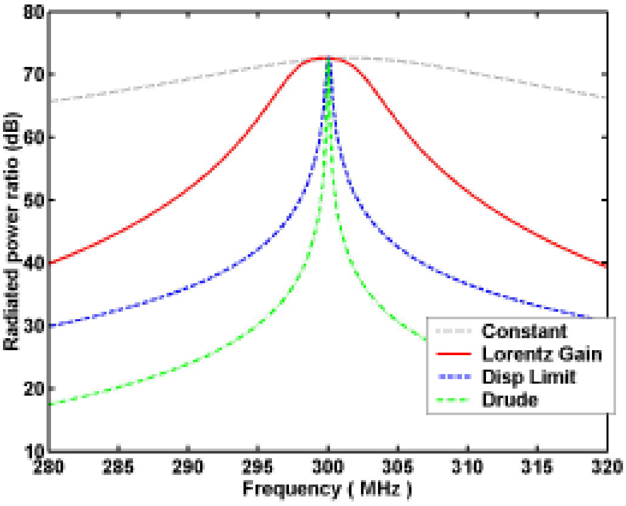

Figure 10. The radiated power ratio (RPR) of an electrically small dipole antenna, driven with a fixed current and surrounded by an electrically small matched ε-negative spherical shell, the permittivity of which was described by several different dispersion models.

For the hypothetical nondispersive, lossless, center-fed-dipole/(glass-ε-negative plasma-glass) spherical-shell system, the input impedance of which is shown in Figure 9, the fractional half-power VSWR bandwidth was $FBW_{VSWR} = 13.16\%$, and the corresponding quality factor was $Q_{VSWR}(\omega_0) = 2/FBW_{VSWR}(\omega_0) = 15.19$. The derivative values of the resistance and reactance curves in Figure 9 were also used to calculate the Yaghjian and Best formula for Q [26]:

$$Q_{YB} \approx f_0 \left|\partial_f Z_{input}(f_0)\right| / 2R(f_0) \approx 15.53 .$$

This value gives the so-called fractional conductance bandwidth, $FBW_{CD} = 1/Q_{YB} = 6.44\%$, which is approximately half of the half-power VSWR fractional bandwidth value [26]. The analytical infinitesimal dipole-(glass-plasma-glass) spherical-shell system predicted a fractional bandwidth of $FBW_{Analytical} = 6.26\%$ and a quality factor of $Q_{Analytical} = 15.964$. The corresponding Chu-limit values, with $ka = 0.074936$, were $Q_{Chu} = 2389.71$ and $FBW_{Chu} = 0.042\%$. When dispersion – which is always present in any realistic metamaterial – is taken into account, these metamaterial-based antenna Q and bandwidth results change dramatically. Unfortunately, we were unable to investigate the corresponding dispersion effects with the *HFSS* models. The requisite very slight changes in frequency and the corresponding smaller changes in permittivity values were extremely difficult to resolve with the *HFSS* models, even on high-performance workstations. On the other hand, they were readily included in the analytical results. As this example shows and as was established in [22], the Q results obtained with the analytical model of the ideal system were larger than those obtained from the numerical models of the more realistic system. We therefore feel that the use of the analytical models to study the effects of dispersion on the quality factors and bandwidths of these metamaterial-based antenna systems, checking with the numerical models whenever possible, is a reasonable approach.

The radiated power ratio values for the infinitesimal dipole-(single layer ε-negative) shell case associated with Figure 8, when the dispersive nature of the ε-negative medium was taken into account, are shown in Figure 10 as a function of the source frequency. For example, it was found that with a lossless Drude ε-negative medium model, $Q_{Drude} = 3947.5 \approx 1.56\ Q_{Chu}$ and $FBW_{Drude} = 0.025\% \approx 0.64\ FBW_{Chu}$. However, for practical applications, one would ideally wish to achieve the quality factor and bandwidth associated with the nondispersive, lossless ε-negative medium case: $Q_{Const} = 14.43 \approx 0.0058\ Q_{Chu}$ and $FBW_{Const} = 6.93\% \approx 173.03\ FBW_{Chu}$. Can one achieve a bandwidth better than the value predicted by the Chu limit in the presence of dispersion? As discussed in [23], if a dispersion-limit model that satisfies the constraint of Equation (2) is used to describe the dispersion of the ε-negative material, in principle the analytical model then gives $Q_{Disp\ limit} = 1622.63 \approx 0.64\ Q_{Chu}$ and $FBW_{Disp\ limit} = 0.062\% \approx 1.56\ FBW_{Chu}$. Moreover, by considering the ε-negative layer to be an active metamaterial medium – described by a Lorentz-Lorentz gain doublet permittivity model created with two Lorentz resonances, one active (frequency above the operating frequency) and one passive (frequency below the operating frequency) [24] – the analytical results give $Q_{Lorentz\ gain} = 35.58 \approx 0.014\ Q_{Chu}$ and $FBW_{Lorentz\ gain} = 2.81\% \approx 71.33\ FBW_{Chu}$, which begin to approach the non-dispersive ε-negative medium values. Thus, the introduction of dispersion-engineered gain (active) metamaterials into the electrically small resonant-dipole-multilayer ε-negative spherical-shell systems would allow one to realize bandwidths that would be quite interesting for a variety of applications. Consequently, by incorporating active metamaterials, in principle there may be a means of achieving not only an efficient electrically small antenna, but one with interesting bandwidth characteristics. Proof-of-concept experiments to study these metamaterial-based electrically small antenna system performance characteristics are currently in the planning stages.

3. Applications of ENZ and MNZ Materials

While the combination of negative and positive materials may induce quasi-static interface resonances that lead to several exciting applications, as described in the previous sections, plasmonic materials with a low relative permittivity, low relative permeability, or low (or even a zero) index of refraction may show other interesting features. As for the dispersion requirements, it should be noted that materials with ε -near-zero or μ -near-zero properties may have a larger bandwidth of operation when compared to negative-index materials, along with lower losses.

3.1 Transparency Using Metamaterials

Low-valued permittivities and/or permeabilities ensure a local negative electric and/or magnetic polarizability, with interesting potential applications. The polarization vectors $\mathbf{P} = (\varepsilon - \varepsilon_0)\mathbf{E}$ and $\mathbf{M} = (\mu - \mu_0)\mathbf{H}$ are, in fact, anti-parallel with the electric and magnetic fields, if $\varepsilon < \varepsilon_0$ or $\mu < \mu_0$, respectively. This behavior may affect the scattering and radiating properties of objects made of such low-value materials. For example, if its polarizability is negative, the scattered field from an object with a scattering cross section that is dominated by the dipolar field will flip its phase. This implies that covering an object with a suitably designed cover may reduce the overall scattering cross section, making the covered object essentially transparent to an external observer, even in its near field [27]. This is in some manner the dual phenomenon of the resonant scattering described in the previous paragraph, even though this cancellation of the scattering relies on a different physical phenomenon. Not being a highly resonant phenomenon in this case, the sensitivity to losses and to the frequency variation is reduced and less pronounced than for the enhanced scattering of the complementary core-shell systems, described above.

As an example, Figure 11 shows the scattered and total field from a dielectric sphere of radius $\lambda_0/4$ (on the left), and for the same sphere covered with an ε -near-zero cover (on the right), projected on a square screen of dimensions $6\lambda_0 \times 6\lambda_0$. Similar results may be obtained for metallic objects and perfect conductors [27].

3.2 Transmission Enhancement through Sub-Wavelength Apertures

ε -near-zero and μ -near-zero covers may be employed to drastically enhance the transmission through a sub-wavelength aperture in a flat, opaque screen, overcoming the diffraction limit. An isolated sub-wavelength aperture generally does not provide good power transmission, which, in the quasi-static limit, is proportional to the fourth power of its electrical size. Covering the hole and the screen with properly designed materials at the entrance and exit side of the aperture, the transmission may be enhanced by several orders of magnitude. The enhancement of the transmitted

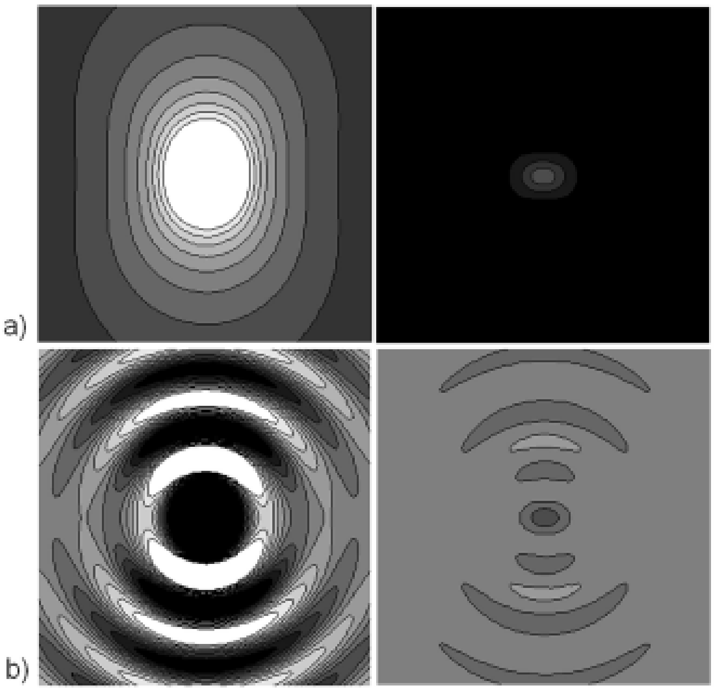

Figure 11. The (a) scattered and (b) total fields from a dielectric sphere of radius $\lambda_0/4$ with permittivity $\varepsilon = 10\varepsilon_0$ (left column), and of the same sphere covered with an ε -near-zero material (right column), designed following the theory described in [27], and projected on a square screen of dimensions $6\lambda_0 \times 6\lambda_0$ placed $0.5\lambda_0$. The field levels have the same scale in the left and right columns.

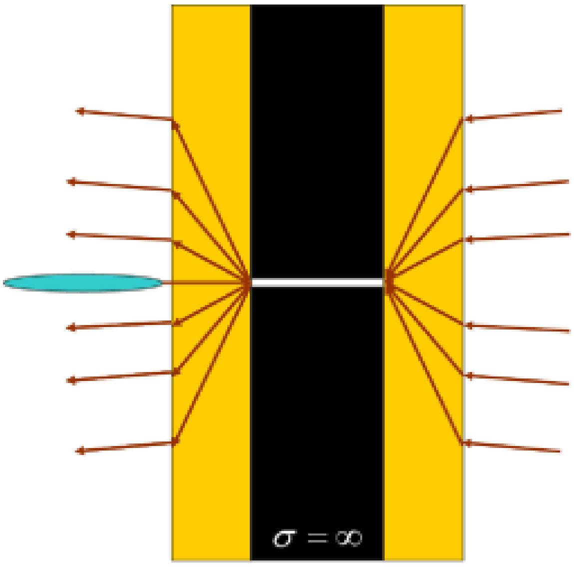

Figure 12. A heuristic ray-theory interpretation of the enhancement that can be obtained by using a metamaterial cover slab having an index of refraction less than that of free space on both sides of the hole.

power relies on the fact that the grounded ε-near-zero and μ-near-zero layers support highly directive leaky waves. As reported in [28, 29], these leaky waves can collect the impinging power at the entrance side of the screen, then tunnel it through the tiny aperture, further help this tunneling at the exit side, and finally reshape the beam to enhance its directivity towards a preferred direction. The combination of these effects may dramatically enhance the total transmitted power.

Figure 12 shows a heuristic picture of this enhancement phenomenon, explained in terms of ray theory. Due to the low refraction index inside the materials, rays are bent towards the normal at the interface between the low-positive material and free space. This enhances the power reception on the entrance side, and the directivity at broadside on the exit side.

3.3 Applications to Antenna Setups

The focusing properties of materials with a low index of refraction may be applied to antenna problems to improve their performance. The concepts exploited in the previous paragraph may be directly applied to build leaky-wave antennas, as has been proposed in [30]. When combined with the phase-compensation effects exploited in the previous paragraph, this may provide a new generation of leaky-wave antennas with low profile and high directivity. It has been shown that single-negative grounded bi-layers with low values of their constitutive parameters may, in fact, support highly directive leaky waves in a sub-wavelength cross section. Also, a similar effect has been studied in cylindrical geometries. A coaxial sub-wavelength shell of low-ε-negative material has been theoretically shown to support a leaky wave that is omnidirectional in the azimuthal plane and directive in elevation angle, and which may be suitable for some applications [31].

The use of ε-near-zero and μ-near-zero metamaterials to achieve highly directional properties of the radiated fields has also been considered in the limit of a matched zero-index media [32]. By having the permittivity and permeability simultaneously be both at or near zero, the medium is matched to free space. A source in such a medium will generate essentially a spatially-static field structure, which has a uniform phase value throughout the medium and, hence, at the output face. Moreover, there is no reflection loss at the interface, since the source and output media are matched. An aperture with a uniform phase distribution will produce the highest-directivity output beam. This behavior is illustrated in Figure 13, with snapshots in time predicted by an FDTD simulation of the

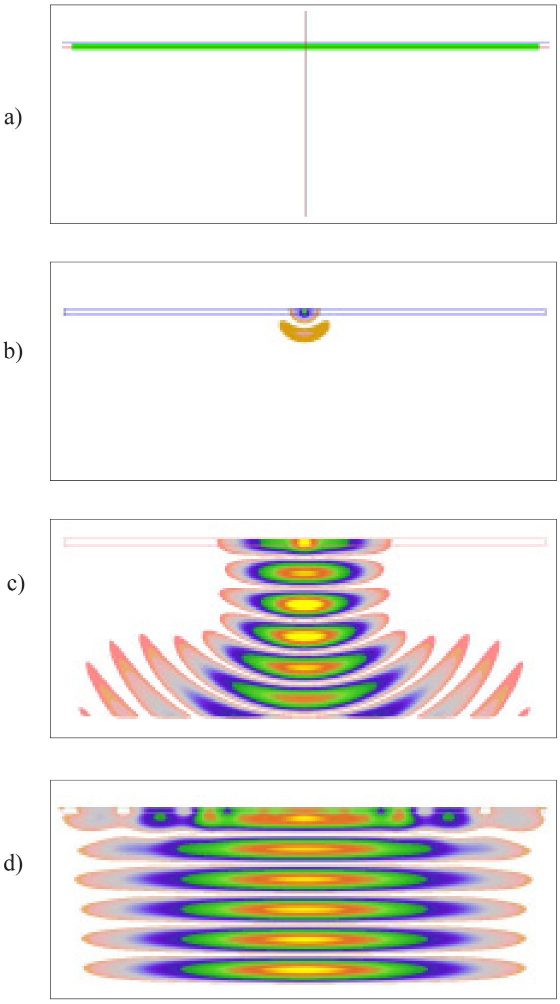

Figure 13. The electric field intensity radiated by a line source centered in a $\lambda_0/10$ thick zero-index slab that was terminated in a PMC sheet: a) $t=0$, b) $t=167\,\Delta t$, c) $t=1000\,\Delta t$, and d) $t=4833\,\Delta t$ (from [32], ©2005, The Institute of Electronics, Information, and Communications Engineers).

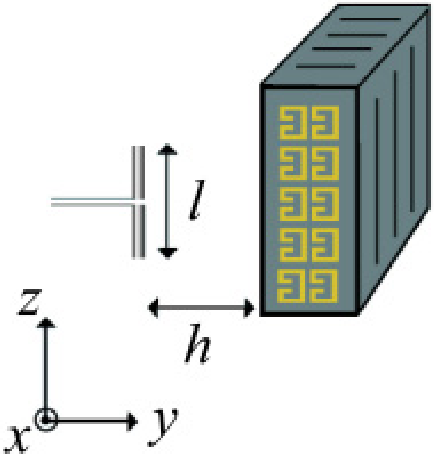

Figure 14a. The geometry of a CLL-based artificial magnetic conductor block, which will act as an in-phase reflector for a low-profile dipole antenna near it.

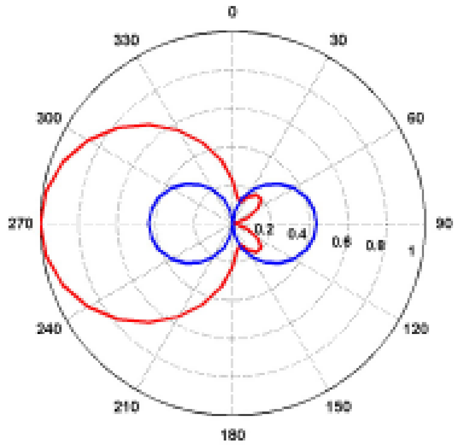

Figure 14b. The E-plane pattern for the geometry of Figure 14a compared to the dipole radiating in free space.

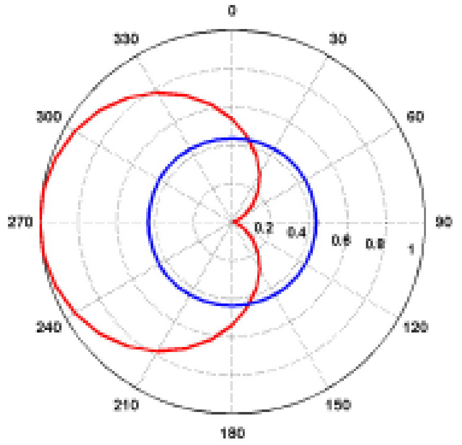

Figure 14c. The H-plane pattern for the geometry of Figure 14a compared to the dipole radiating in free space.

electric-field intensity generated by a line source in a zero-index slab that is backed with a perfect magnetic conductor (PMC) surface (the PMC surface did not short out the uniform electric field in the slab) [33]. The fields propagated away from the source, creating a spatially uniform field in the zero-index medium once steady state was reached. At that time, the output beam was generated from a uniform field distribution across the entire output face of the finite slab. This behavior has been demonstrated with electromagnetic bandgap (EBG) structures [34].

3.4 Large ENG or MNG Material Responses

Another antenna application for metamaterials that has stimulated much interest is the concept of an artificial magnetic conductor, i.e., an in-phase reflector. This can be achieved with a μ-negative material with a large permeability, or an ε-near-zero material. A wide variety of artificial-magnetic-conductor (AMC) realizations has been considered, and these include mushroom surfaces [35, 36], frequency-selective surfaces (FSSs) and EBG surfaces [36, 37], and space-filling curves [38]. All of these classes of artificial magnetic conductors include a PEC ground plane and thus at least guarantee high reflectivity. In contrast, in [39] an artificial magnetic conductor was realized with only the capacitively-loaded-loop- (CLL) based μ-negative material shown in Figure 14a, i.e., there was no ground plane. This aspect demonstrates that the response of the μ-negative material can be made large enough by itself to realize the requisite in-phase reflectivity. Moreover, the associated surface modes are dramatically different from those associated with the ground-plane varietals. These artificial magnetic conductors are highly desired for achieving low-profile antennas, i.e., an antenna such as shown in Figure 14a can be placed in very close proximity to the artificial magnetic conductor without it being shorted out, as it would be in the presence of a PEC. The predicted radiation patterns for a dipole antenna near the capacitively-loaded-loop-based artificial magnetic conductor block are compared to those of a dipole radiating in free space in Figures 14b and 14c. Current investigations into these various artificial magnetic conductor surfaces include decreasing their thicknesses; achieving active substrates to realize multi-band and tunable artificial magnetic conductors; achieving very high front-to-back ratios; and various aspects of array applications, such as beam steering and the mitigation of scan blindness.

4. Conclusions

Materials with anomalous values of their constitutive parameters have been shown to possess interesting potential in the design and engineering of next-generation structures for guiding, scattering, and radiating applications. Resonances arising in electrically small regions of space, where negative materials are paired with common dielectrics, present great potential for overcoming the limits generally associated with several electromagnetic problems, by providing a means to engineer the overall responses of the systems. Low-refraction materials, despite their non-resonant character, may also have a strong impact in some applications, since they combine anomalous wave interaction with relatively larger bandwidth and lower losses.

The metamaterials research area has evolved into prominence only very recently. Nonetheless, it is already having a large impact on our electromagnetics community. Metamaterials have revitalized our interest in complex media, and in their analysis and numerical modeling. There have been large strides in our understanding of the anomalous behaviors of these materials, and in our potential utilization of their exotic properties in many electromagnetic applications, from the microwave to the optical regime. We have briefly reviewed here some of what has already been learned about several aspects of these topics; we look forward to further progress in the future.

5. Acknowledgments

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A Common Framework for Computational Electromagnetics on Three-Dimensional Grids

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Abstract

We review some representative grid-based simulation approaches for electromagnetic fields, namely the Finite Integration Technique (FIT), the Finite-Difference (FD) method, and the Finite-Element (FE) method. Recent research has revealed that these methods have strong mutual relations, and even coincide in some important cases. The theoretical framework and elegant notation of the FIT is shown to build a common basis for all three methods, and allows analyzing their similarities and differences. Finally, recently proposed sub-cell methods are discussed as one of the most important improvements concerning the modeling accuracy and efficiency of this class of simulation methods.

1. Grid-Based Discretization Methods

The main idea of the *discretization* of electromagnetic-field problems is their transformation from the infinite-dimensional, continuous world into a *discrete* formulation with a finite number of dimensions, which fits into a computer program. One possible step in this reduction of the problem's dimensions is to specify a limited computational domain, and therein a finite number of sampling points for the computed field values. This defines the computational grid. Depending on the method to be applied, the next steps of the discretization process may be the reduction of the functional solution space, the transformation of differential expressions in Maxwell's equations into difference formulas, or even such steps as the limitation of number space by a floating-point representation of numbers.

If we concentrate on boundary-value problems that are characterized by a possibly complicated geometric form of the boundaries and a strongly inhomogeneous material distribution within the computational domain, a well-established class of discretization approaches includes the so-called volume-grid methods: Here, a three-dimensional computational grid is defined, covering the complete domain, and thus allowing a nearly arbitrarily inhomogeneous material distribution. However, note that the material distribution and the corresponding geometrical objects are sometimes represented by different grids (e.g., a surface triangulation), or even by different models, such as an analytical description of solids.

The most popular discretization methods for volume grids used today are based on the early work of K. S. Yee (1966, [1]), T. Weiland (1977, [2]), and J. C. Nedelec (1980, [3]). In this paper, we review the resulting simulation approaches as the main representatives of this class of methods, namely the Finite-Difference Time-Domain (FDTD) method, the Finite-Integration Technique (FIT), and finally the Finite-Element (FE) method using edge elements. We will also briefly discuss the Cell Method (CM), which was developed independently in the tradition of the early paper of E. Tonti (1975, [4]). Some other approaches based on volume grids that will not be touched on here are the Transmission-Line Matrix (TLM) method [5], and various Finite Volume approaches [6], which have gained interest in computational electromagnetics in recent years.

All methods in this class of approaches are clearly limited if the electrical size of the problem to be solved exceeds some tens to hundreds of wavelengths per space dimension, since the three-dimensional grid must resolve all waves by a certain minimum of grid steps. There exists a large variety of alternative methods for such large-scale

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problems, ranging from the numerical solution of integral equations up to asymptotic methods such as Geometrical or Physical Optics. A detailed discussion of such approaches is beyond the scope of this contribution. Further, we concentrate on the solution of high-frequency problems, where some of the similarities and differences between the methods become particularly obvious. The transformation of most of the results to other regimes, such as statics or eddy-current problems, is straightforward.

The paper is organized as follows. First, we review the basic concepts, how each of the approaches performs a discretization of Maxwellian field problems. It turns out that under some circumstances, the methods have strong mutual relations, and may even coincide with respect to the resulting discrete models. Finally, we put some focus on recently proposed conformal methods within the FIT and FDTD approaches. They have the potential to overcome the staircase modeling error that used to be attached to these methods.

2. Theory of Discretization Methods

In this section, we will briefly review three grid-based simulation methods and their fundamental concepts in discretizing Maxwellian field problems. These are the Finite-Integration Technique, which directly starts with the geometric properties of the equations, and the Finite-Difference and Finite-Element methods, where differential expressions and solution spaces are transformed into discrete forms, respectively. We concentrate on the derivation of the spatial operators and the properties regarding the simulation of high-frequency fields. The semi-discrete systems that arise (i.e., still continuous in time) may be solved in the frequency domain or the time domain by appropriate time-integration schemes.

2.1 Geometric Discretization: Finite-Integration Technique (FIT)

The Finite-Integration Technique (FIT) was proposed by T. Weiland in [2] (detailed descriptions can be found in [7-10]), and has now been used for nearly three decades for the numeric simulation of electromagnetic fields. The main idea is a direct and strictly geometrically motivated discretization of Maxwell's equations in their most general form – contrary to a possible discretization of derived equations. Thus, the FIT is classified as a geometrical discretization method. Recently, it has been shown that the mathematical language of the FIT is also very well suited to describing some related methods, enabling a comparison of these methods in an elegant manner.

The classic derivation of the FIT starts with the integral form of Maxwell's equations, where the integrals of the electromagnetic field vectors, $\vec{E}$ (electric field), $\vec{H}$ (magnetic field), $\vec{D}$ (electric flux density), $\vec{B}$ (magnetic flux density), and $\vec{J}$ (electric current density) on *arbitrary* faces and volumes $A, V \in \mathbb{R}^3$ are related to the corresponding surface integrals on their boundaries $\partial A, \partial V$.

The first discretization step for Faraday's law,

$$\oint_{\partial A} \vec{E} \bullet d\vec{s} = -\int_{A} \frac{\partial}{\partial t} \vec{B} \bullet d\vec{A} \forall \; , \quad A \in \mathbb{R}^3 \, , \qquad (1)$$

is to allow only the finite set of integration areas that are defined by one or a combination of elementary facets of a three-dimensional computational grid (the *primary grid*). Consequently, the evaluation of the line integral is restricted to the edges, L_n, of the grid.

The integrals on single edges or facets are not further resolved at this point of the derivation. They define the finite-dimensional set of state variables of the method:

$$\widehat{e}_n = \int_{L_n} \vec{E}\left(\vec{r}, t\right) \bullet d\vec{s} \; , \; \left(n = 1 \ldots N_L\right) , \qquad (2)$$

$$\widehat{\widehat{b}}_n = \int_{A_n} \vec{B}\left(\vec{r}, t\right) \bullet d\vec{A} \; , \; \left(n = 1 \ldots N_A\right) . \qquad (3)$$

These quantities are referred to as *electric grid voltages* and *magnetic grid fluxes*, respectively. N_L and N_A denote the number of edges and facets of the grid.

The evaluation of the closed line integral in Faraday's law for a single grid facet can now be represented by a combination of the grid voltages defined on its boundary, with the appropriate sign. Summarizing this procedure for all grid facets, and combining all state variables in algebraic vectors $\widehat{\mathbf{e}}$ and $\widehat{\widehat{\mathbf{b}}}$, we obtain the *discrete form of Faraday's law*:

$$\mathbf{C} \widehat{\mathbf{e}}\left(t\right) = -\frac{d}{dt} \widehat{\widehat{\mathbf{b}}}\left(t\right) . \qquad (4)$$

The $N_A \times N_L$ matrix $\mathbf{C}$ describes the incidence relations of the grid (the topological relations between grid facets and the edges defining their boundaries). Within the framework of the FIT, this matrix can be interpreted as a *discrete curl operator*, and thus it is referred to as the *curl matrix* of the grid.

For the discretization of Ampere's law,

$$\oint_{\partial A} \vec{H} \bullet d\vec{s} = -\int_{A} \left(\frac{\partial}{\partial t} \vec{B} + \vec{J} \right) \bullet d\vec{A} \; , \; \forall A \in \mathbb{R}^3 \, , \qquad (5)$$

we can perform a completely analogous derivation, where now the integrations are restricted to the facets $\tilde{A}_n$ ($n = 1 \ldots N_{\tilde{A}}$) of a second computational grid, the so-called *dual grid*. Its main property is a one-to-one correspondence of dual grid objects of dimension l ($l = 1 \ldots 3$) with primary grid objects of dimension $(3 - l)$: e.g., each dual edge, $\tilde{L}_n$ ($l = 1$), intersects one (and only one) primary facet, A_n ($l = 2$), and vice versa. These pairs of primary and dual objects are given the same index and the same orientation.

For a Cartesian primary grid, we obtain a Cartesian dual grid, which is shifted by a half grid step in each direction (a *staggered grid*), with some formal exceptions at the grid boundaries. All dual grid objects are denoted by a tilde, and we have $N_L = N_{\tilde{A}}$, $N_A = N_{\tilde{L}}$, etc.

The magnetic grid voltages, $\hat{h}_n$ (related to dual edges), the electric grid fluxes, $\hat{\hat{d}}_n$, the grid currents, $\hat{\hat{j}}_n$ (related to dual facets), and the electric grid charges, q_n (related to dual cells), are defined as additional state variables on the dual grid. Finally, the *discrete Faraday's law* reads

$$\tilde{\mathbf{C}}\hat{\mathbf{h}}(t) = \frac{d}{dt}\hat{\hat{\mathbf{d}}}(t) + \hat{\hat{\mathbf{j}}}(t). \tag{6}$$

In a similar manner, we also discretize the remaining two Maxwell's equations, where now the volume integrals on primary and dual grid cells are related to a summation of the grid fluxes defined on their boundaries. For all N_V or $N_{\tilde{V}}$ primary or dual grid cells, respectively, we obtain

$$\oint_{\partial V} \vec{B} \bullet d\vec{A} = 0, \quad \forall V \in \mathbb{R}^3 \xrightarrow{V \in \{V_n\}} \mathbf{S}\hat{\hat{\mathbf{b}}} = \mathbf{0}, \tag{7}$$

$$\oint_{\partial V} \vec{D} \bullet d\vec{A} = \int_V \rho dV, \quad \forall V \in \mathbb{R}^3 \xrightarrow{V \in \{\tilde{V}_n\}} \tilde{\mathbf{S}}\hat{\hat{\mathbf{d}}} = \mathbf{q}. \tag{8}$$

The $N_V \times N_A$ and $N_{\tilde{V}} \times N_{\tilde{A}}$ matrices $\mathbf{S}$ and $\tilde{\mathbf{S}}$ are the *discrete divergence matrices* ("source") of the primary and dual grid, respectively.

It has to be noted that this procedure represents a *discretization* of the originally continuous equations in the sense of defining a finite problem dimension. However, up to this point, *no approximations* have been introduced. As a direct consequence, the *Maxwell's grid equations* (MGE) defined by Equations (4), (6), (7), and (8) are generally valid for all kinds of field problems. Additionally, many properties of the continuous Maxwellian theory can be reformulated for the discrete set of state variables. As a famous example, the matrix relations $\mathbf{SC} = \mathbf{0}$ and $\tilde{\mathbf{S}}\tilde{\mathbf{C}} = \mathbf{0}$ – which, at first sight, are purely topological properties of the incidence relations expressed by the operator matrices – now describe the *exact* source-free condition of curl fields ($\operatorname{div}\operatorname{curl} \equiv 0$) on the primary or dual grid, respectively, in a discrete sense. Some more properties concern the conservation of charge and energy, and the orthogonality of eigenmodes [8, 11].

Finally, to complete the FIT formulation, the so-called *discrete material relations* have to be defined, which establish the relationship between the state variables on the two grids. This discretization step introduces the *metrics* of the grids, as well as the unavoidable approximations of the method. For the simplest case of linear and time-invariant constitutional relations, neglecting permanent polarizations, we obtain the algebraic equations

$$\hat{\hat{\mathbf{d}}} = \mathbf{M}_\varepsilon \hat{\mathbf{e}},$$

$$\hat{\hat{\mathbf{b}}} = \mathbf{M}_\mu \hat{\mathbf{h}}, \tag{9}$$

$$\hat{\hat{\mathbf{j}}} = \mathbf{M}_\sigma \hat{\mathbf{e}}.$$

Following from the duality property of the grids, the *generalized material operators* $\mathbf{M}_\varepsilon$, $\mathbf{M}_\mu$, and $\mathbf{M}_\sigma$ can be postulated to be square matrices.

There exist various FIT formulations with different concepts, implementations, and resulting properties of these material operators. In the *classic FIT*, only so-called dual-orthogonal grids are allowed, where all pairs of edges and facets of the grids intersect at 90°. Here, the integral definition of the state variables can be reduced to continuous field components at the intersection points, using local approximation formulas. This leads to simple material matrices in diagonal form, featuring a one-to-one correspondence of pairs of voltages and fluxes:

$$\frac{\hat{\hat{d}}_i}{\hat{e}_i} \approx \frac{\int_{\tilde{A}_i} \varepsilon \, dA}{\int_{L_i} ds} = \frac{\bar{\varepsilon}_i \tilde{A}_i}{L_i} = M_{\varepsilon,ii} \tag{10a}$$

$$\frac{\hat{h}_i}{\hat{\hat{b}}_i} \approx \frac{\int_{\tilde{L}_i} \mu^{-1} \, ds}{\int_{A_i} dA} = \frac{\overline{\mu_i^{-1}} \tilde{L}_i}{A_i} = M_{\mu^{-1},ii}. \tag{10b}$$

These formulas naturally introduce mean permittivities, $\bar{\varepsilon}_i$, averaged over dual faces, and mean inverse permeabilities, $\overline{\mu_i^{-1}}$, averaged over dual edges. The operators show a high accuracy and, most notably, a high efficiency, which will be discussed in more detail below.

The most important representative of dual-orthogonal grids is the Cartesian grid type [7], but there are also implementations of the classic FIT for cylindrical grids [7], special tetrahedral grids [12], and (two-dimensional) triangular grids [13]. An extension of the FIT to nonorthogonal grid pairs has been proposed in [14], and leads to sparse, non-diagonal material matrices.

It will be shown below that under certain prerequisites, some other discretization methods, such as Finite Elements or the Cell Method, can be described in the notation of the FIT by just replacing the material matrices. This surprising result includes the fact that the so-called *topological* matrix operators $\mathbf{S}, \mathbf{C}$, and $\tilde{\mathbf{S}}, \tilde{\mathbf{C}}$, which model the geometry of Maxwell's equations on the two computational grids, are generally valid, and thus build the basis of a *discrete electromagnetic field theory*.

On the other hand, if the material matrices are the central point where these methods differ, we need some rules regarding how to construct them, and how to assess their validity as well as their efficiency for a given field problem. One such rule can be formulated as a consequence of the discrete eigenvalue equation for lossless problems:

$$\operatorname{curl} \mu^{-1} \operatorname{curl} \vec{E} = \omega^2 \varepsilon \vec{E} \quad \leftrightarrow \quad \tilde{\mathbf{C}} \mathbf{M}_\mu^{-1} \mathbf{C} \hat{\mathbf{e}} = \omega^2 \mathbf{M}_\varepsilon \hat{\mathbf{e}} \cdot \tag{11}$$

Applying the duality property $\tilde{\mathbf{C}} = \mathbf{C}^T$, we find that *symmetric positive definite* material operators are a sufficient condition for the stability of the discretization scheme [8, 14, 15]. Assuming that the operators are additionally locally *consistent*, this ensures the *convergence* of the method.

A more practical (but still important) requirement is related to the efficiency of the method: If we want to transform Equation (11) from a general into a standard eigenvalue problem – which is considerably easier to solve – the inverse, $\mathbf{M}_\varepsilon^{-1}$, of the permittivity matrix has to be available. Its existence follows from the symmetric positive definite property already mentioned, but the ideal case to compute it is given for the diagonal matrices, Equation (10), of dual-orthogonal grid systems. A similar criterion can also be formulated for the time-domain schemes discussed later: Again, the inverse operators are needed to obtain an *explicit* algorithm with superior efficiency properties. (For the same reason, we directly build the *inverse* permittivity matrix in the nonorthogonal algorithm mentioned above.)

2.2. Discretization of Differential Operators: Finite-Difference (FD) Method

We only consider here one representative out of the class of Finite-Difference (FD) methods, which is well-known for its success in simulating high-frequency electromagnetic fields: the Finite-Difference Time-Domain (FDTD) method. It was first proposed by K. S. Yee in 1966 [1], and it has been referred to as the FDTD since the beginning of the 1980s [16]. An outline of the historical development of the FDTD (*Yee's method*) can be found in [17, 18].

Again, Maxwell's equations are directly transformed into a discrete form, but now we start with their differential formulation and the spatial differential operators "curl" and "div." The pioneering idea in [1] was to allocate the three components of the electric and magnetic field vectors not at one common point in space, but separately, at the centers of the edges of a Cartesian grid and the corresponding dual grid. This is the *discretization step* of the method. In the following *approximation step*, the differentiations in the "curl" operations of Faraday's law are replaced by central-difference formulas. In the typical notation of the FDTD, with indices i, j, k for the grid lines in the x, y, z direction, and with grid step widths $\Delta x, \Delta y, \Delta z$, we obtain, e.g. (cf. Figure 1b),

$$\left[\frac{\partial}{\partial x} E_y - \frac{\partial}{\partial y} E_x \right]_{i+\frac{1}{2}, j+\frac{1}{2}, k}$$

$$\approx \frac{E_{y,i+1,j+\frac{1}{2},k} - E_{y,i,j+\frac{1}{2},k}}{\Delta x}$$

$$- \frac{E_{x,i+\frac{1}{2},j+1,k} - E_{x,i+\frac{1}{2},j,k}}{\Delta y} . \tag{12}$$

Further on, a staggered grid is also introduced for the time axis, where the magnetic components are allocated at *full* time steps, $H^n = H\left(t_0 + n\Delta t\right)$, and the electric components at *half* time steps $E^{n+\frac{1}{2}} = E\left[t_0 + \left(n + \frac{1}{2}\right)\Delta t\right]$. Again, we can use a central-difference expression for the time derivatives, which *discretizes* and *approximates* the equations with respect to their time dependency. Finally, by simple manipulations, we obtain the *update equations* of the FDTD. They constitute an explicit time-integration algorithm, the so-called *leapfrog scheme*. For one component, this reads

$$H^{n+1}_{z,i+\frac{1}{2},j+\frac{1}{2},k} = H^{n}_{z,i+\frac{1}{2},j+\frac{1}{2},k}$$

$$- \frac{\Delta t}{\mu} \left(\frac{E^{n+\frac{1}{2}}_{y,i+1,j+\frac{1}{2},k} - E^{n+\frac{1}{2}}_{y,i,j+\frac{1}{2},k}}{\Delta x} \right.$$

$$\left. - \frac{E^{n+\frac{1}{2}}_{x,i+\frac{1}{2},j+1,k} - E^{n+\frac{1}{2}}_{x,i+\frac{1}{2},j,k}}{\Delta y} \right) . \tag{13}$$

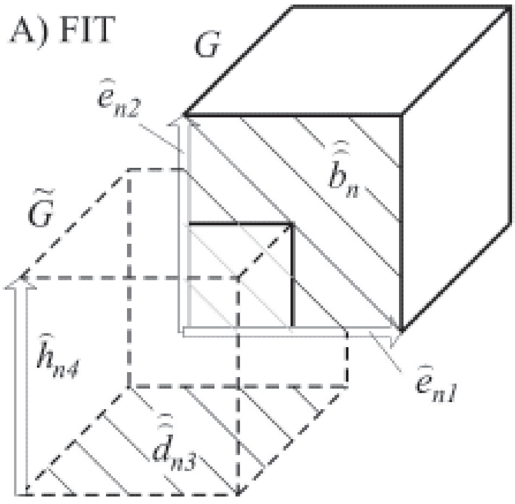

Figure 1a. The allocation of components in the FIT.

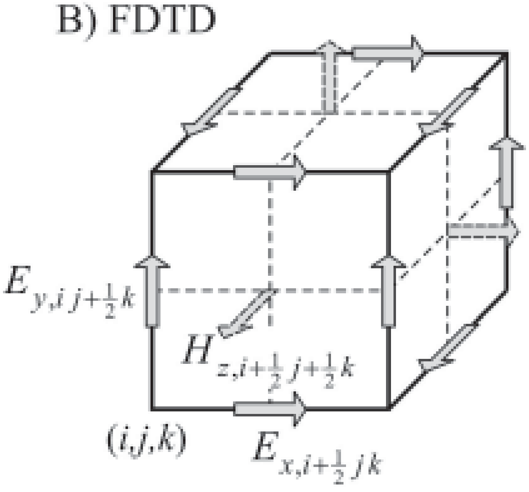

Figure 1b. The allocation of components in the FDTD.

2.3. Equivalence of the FIT and FDTD schemes

Figure 1 shows a comparison of the allocation of grid voltages in the FIT – defined as integrals on complete edges (A) – and the FDTD field components, at the center of these edges (B). After formally relating components (FDTD) to grid voltages (FIT) on a Cartesian mesh by (for the electric field, cf. again Figure 1)

$$E_{x,i+\frac{1}{2},j,k}\Delta x \leftrightarrow \widehat{e}_{n1}\,, \tag{14}$$

$$E_{y,i,j+\frac{1}{2},k} \leftrightarrow \widehat{e}_{n2}\,,$$

it becomes obvious that one curl operation in the FDTD (here, for the update of the magnetic component, $H_{z,i+\frac{1}{2},j+\frac{1}{2},k}$) and one circulation in the FIT (here, around the facet with grid flux $\widehat{\widehat{b}}_n$) are based on an equivalent choice of discrete components. This result can be interpreted as an application of Stokes' law to the finite operations.

Accordingly, the Maxwell Grid Equation of the FIT can be discretized using the same staggered time axis as in the FDTD and the leapfrog time-integration scheme. In vector notation (neglecting all currents), we obtain the update equations

$$\widehat{\mathbf{h}}^{n+1} = \widehat{\mathbf{h}}^{n} - \Delta t \mathbf{M}_{\mu}^{-1}\mathbf{C}\widehat{\mathbf{e}}^{n+\frac{1}{2}}\,, \tag{15a}$$

$$\widehat{\mathbf{e}}^{n+\frac{3}{2}} = \widehat{\mathbf{e}}^{n+\frac{1}{2}} + \Delta t \mathbf{M}_{\varepsilon}^{-1}\widetilde{\mathbf{C}}\widehat{\mathbf{h}}^{n+1}\,. \tag{15b}$$

Using Equation (14) for single components, these can easily be transformed into the FDTD scheme of Equation (13). Thus, on the computational level, the two schemes coincide.

From the FIT point of view, the FDTD approach (as well as other finite-difference schemes) appears to be a special case for Cartesian grids with a specific time-integration scheme. Similarly, the FIT can also be interpreted as an alternative derivation of the update equations of the FDTD. Thus, in spite of their conceptual differences, the FIT (on Cartesian grids with the leapfrog scheme) and the FDTD are often referred to as *computationally equivalent*.

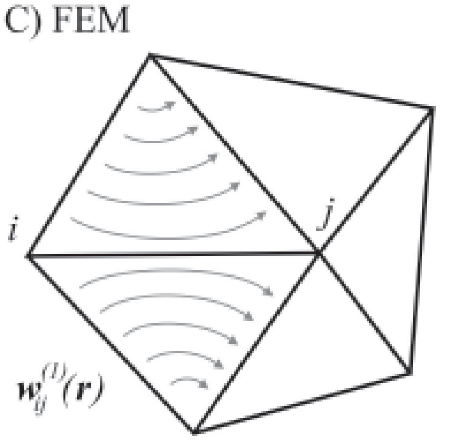

Figure 1c. The, basis functions (Whitney edge elements) of the FE.

However, it should be noted that the basic FDTD derivation in the form given above is only valid for the simplest case of Cartesian grids. For the practical application of the FDTD, a number of extensions are typically needed. They may be as simple as the implementation of nonuniform Cartesian grids or the averaging of material parameters at interfaces, and may reach up to the more complicated sub-cell methods discussed below, or the application of more general grids, e.g. for rotationally symmetric structures. It turns out that many of these extensions do not easily fit into the differential calculus of Yee's original formulation, but are typically derived using local integrations (circulations), i.e., the FIT concept. Examples can be found in [19, 20], sometimes referred to as the *Contour-Path FDTD*.

Further, the notation with operator matrices is not very common in the FDTD literature (but, of course, possible, due to the computational equivalence), which makes the analysis of some key properties of the method sometimes difficult. The same is true for the smaller set of state variables, which in FDTD only exist for field quantities (but not for the fluxes). As a consequence, the separation of exact topological operators from the material matrices (with all approximations) is not visible in the FDTD notation.

An important property of the time-domain formulation that is shared by both methods is the conditional stability of the leapfrog scheme. The recursion formulas are only stable if the time step, Δt, is not larger than the upper limit defined by the *Courant-Friedrich-Lewy* criterion [21]. This is given by the largest eigenvalue, ω_{max}, of the system matrix, and can be estimated (in the Cartesian case) by the grid steps and the material values in the mesh [1, 22]:

$$\Delta t_{max} = \frac{2}{\omega_{max}} \approx \min_n \sqrt{\frac{\varepsilon_n \mu_n}{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \ . \qquad (16)$$

Further, the orders of the local consistency errors of both approximations are identical [18].

2.4. Discretization of Functional Spaces: Finite Elements (FE)

A basically different path for the discretization of electromagnetic field problems is followed in the Finite-Element (FE) method. The starting point here is often a derived equation, e.g., the lossless Helmholtz equation in the frequency domain,

$$\nabla \times \frac{1}{\mu} \nabla \times \vec{E} - \omega^2 \varepsilon \vec{E} = -j\omega \vec{J} \ . \qquad (17)$$

All field vectors are now complex quantities (phasors), representing fields with the time-harmonic dependency $e^{j\omega t}$.

The unknown electric field, $\vec{E}(\vec{r})$, a complex-valued vector function in $\vec{r}$, is searched for as an element of the functional solution space, V. Typically this space is defined as the space of *curl-conformal* functions, i.e., the space $V = H^{\text{curl}}(\Omega)$ of all functions defined on the problem domain $\Omega \subset \mathbb{R}^3$, the curls of which are square-integrable on Ω. This space is adjusted to the given boundary conditions on $\partial\Omega$ (see, e.g., [23]).

In order to obtain a finite-dimensional representation, FE methods perform two steps that can be interpreted as *discretizations*, as discussed above. First, the original Equation (17) is replaced by a so-called *weak formulation*, introducing a finite number of *weight functions*, $\vec{w}_i(\vec{r}) \in W$:

$$\left\langle \nabla \times \frac{1}{\mu} \nabla \times \vec{E} - \omega^2 \varepsilon \vec{E}, \vec{w}_i \right\rangle = -j\omega \left\langle \vec{J}, \vec{w}_i \right\rangle \qquad (18)$$

($i = 1 \ldots N_W$). Herein, the scalar product of the functions $\vec{v} \in V$, $\vec{w} \in W$ is defined by the integration $\langle \vec{v}, \vec{w} \rangle = \int_\Omega \vec{v}(\vec{r}) \bullet \vec{w}(\vec{r})\, dV$. Next, we replace the searched-for electric field in this equation (or, to be more precise, its FE approximation) by a superposition of a finite number of *basis functions*, $\vec{v}_j \in V_h$ ($j = 1 \ldots N_V$):

$$\vec{E}(\vec{r}) = \sum_j e_j \vec{v}_j(\vec{r}) . \qquad (19)$$

The space, $V_h \subset V$, spanned by these functions has to be an appropriate approximation of the original functional space: this is the specific discretization process of FE. After some manipulations (and under some prerequisites, e.g., for the boundary conditions) we obtain an algebraic equation for the unknown coefficients (the *degrees of freedom*, DoF), e_j:

$$\left(\mathbf{K} - \omega^2 \mathbf{M}\right)\mathbf{e} = \mathbf{r} \ . \qquad (20)$$

The *stiffness matrix*, $\mathbf{K}$, and the *(electric) mass matrix*, $\mathbf{M}$, are given by

$$K_{ij} = \int_\Omega \frac{1}{\mu} \left(\nabla \times \vec{v}_j\right) \bullet \left(\nabla \times \vec{w}_i\right) dV \ , \qquad (21a)$$

$$M_{ij} = \int_\Omega \varepsilon \vec{v}_j \bullet \vec{w}_i \, dV \ , \qquad (21b)$$

and the right-hand side, $\mathbf{r}$, follows from the excitation currents, $\vec{J}$, in Equation (18).

An important step in this derivation is the proper choice of the basis and weight functions. Using the *Ritz-*

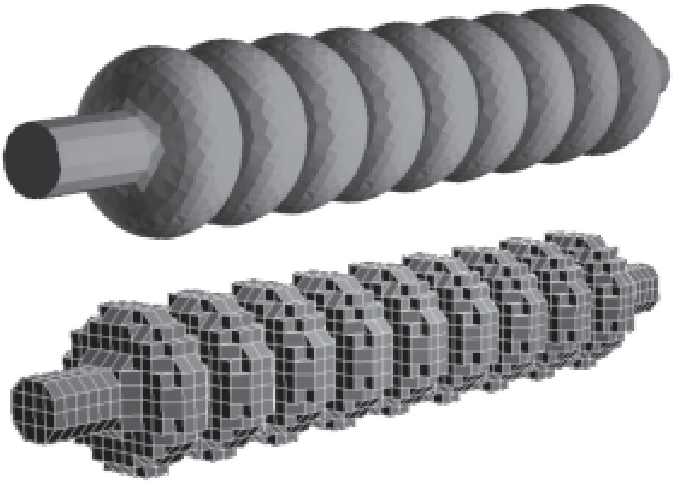

Figure 2. A nine-cell cavity from the TESLA project [25]: conformal and staircase grid models.

Galerkin approach, these functions are chosen to be identical, $\vec{w}_i \equiv \vec{v}_i$, which leads to symmetric system matrices in Equation (20). Further, $\mathbf{K}$ and $\mathbf{M}$ are sparse matrices if functions with local support are used that have nonzero values only in a small number of cells of the computational grid (cf., Figure 1c). These local basis functions are the *finite elements* that gave the method its name. Finally, another criterion is the consistency of the method, which is typically ensured by a proper choice of basis functions with a low polynomial grade.

2.5. Relations between the FIT and FE approaches

Comparing the classic formulations of the FIT and the FE in the light of practical simulations for high-frequency electromagnetic fields, we can identify two important and prominent main differences, which may summarized as *efficiency versus modeling flexibility*. The classic FIT with its dual-orthogonal grids (including the special case of the FDTD) has the advantage of diagonal (and easily invertible) material operators, leading to an efficient explicit algorithm in the time domain. As we will discuss below, the mass matrices of the FE play a role similar to these material operators, but they are generally non-diagonal. Consequently, FE time-domain schemes are always implicit in the sense that they require a matrix inversion in each time step.

On the other hand, the FE has lower demands on the properties of the computational grid, compared to the FIT and FDTD (since no dual grid is needed in the derivation). The most popular grid type, e.g., tetrahedral grids, can typically be used without severe limitations, leading to superior flexibility in modeling complex structures and material inhomogeneities. Compared to the so-called *staircase* approximation of oblique interfaces using Cartesian grids (cf. [24] and Figure 2), we often obtain increased accuracy with a considerably smaller number of mesh cells.

The search for a synthesis of both methods – or, to be more specific, for an explicit time-domain scheme for general computational grids – has been an important motivation for the intensive research that has been performed on the theory of grid-based methods during the last decade.

2.5.1 Basic Analogies Using Edge Elements

At first sight, the global approach of the FE seems to have no obvious relationship to the local concepts of the FIT and FDTD. However, this changes if so-called *edge elements* [3] (cf. Figure 1c) are used as basis functions in the FE. Today, these edge elements are typically introduced as part of the so-called *Whitney* complex [26], which provides special local functions for each type of the grid objects of a tetrahedral mesh (vertices, edges, facets, and cells, with dimensions $l = 0,1,2,3$, respectively).

For $l = 0$, these are the (scalar) barycentric coordinates in each cell, $w_j^{(0)} = \lambda_j\left(\vec{r}\right)$. These so-called *nodal elements* are used to construct the (vector-valued) *edge elements* ($l = 1$) and *face elements* ($l = 2$):

$$l = 1 : \vec{w}_{ij}^{(1)} = w_i^{(0)} \nabla w_j^{(0)} - w_j^{(0)} \nabla w_i^{(0)} , \qquad (22)$$

$$l = 2 : \vec{w}_{ijk}^{(2)} = w_i^{(0)} \nabla w_j^{(0)} \times \nabla w_k^{(0)}$$

$$+ w_j^{(0)} \nabla w_k^{(0)} \times \nabla w_i^{(0)} \qquad (23)$$

$$+ w_k^{(0)} \nabla w_i^{(0)} \times \nabla w_j^{(0)} .$$

In these formulas, the indices i, j, k denote the vertices defining the edge and facet considered, respectively.

The important advantages of this set of functions include their tangential or normal continuity over the element (and possible material) interfaces, and the so-called *exact sequence* property of the corresponding functional spaces. In this context, the functions defined by Equation (22) can be identified as the lowest-order representatives of the more general class of H^{curl} : conformal finite elements. We will not discuss these important properties here; more details can be found, e.g., in [23].

As indicated by their name, each of these basis functions is associated with a single edge (or facet) of the grid, where its integral value is nonzero. After proper normalization, we have

$$\int_{L_i} \vec{w}_j^{(1)}(\vec{r}) \bullet d\vec{s} = \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases}, \tag{24a}$$

$$\int_{A_i} \vec{w}_j^{(2)}(\vec{r}) \bullet d\vec{s} = \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases}. \tag{24b}$$

With Equation (19) and the comparison to Equation (2), this directly leads to the equivalence relation $e_i \equiv \widehat{e}_i$ between the degrees of freedom of the FE and the electric grid voltages of the FIT.

If we use the $\vec{w}^{(2)}$ functions as additional basis functions for the magnetic flux density (in the sense of *Mixed Finite Elements*, [27]), this equivalence is also valid for the magnetic grid fluxes in Equation (3). However, it should be noted that these relations cannot be easily retained if edge elements with a higher polynomial order are used, where we have more than one degree of freedom per grid object (edge or facet).

Finally, we can proceed in these analogy considerations and analyze the system matrices of the FE. Using the definition of face elements in Equation (23), the FE stiffness matrix in Equation (21a) can be expressed in the FIT notation by

$$\mathbf{K} = \tilde{\mathbf{C}}\mathbf{M}_{1/\mu}^{(FE)}\mathbf{C} \tag{25a}$$

with

$$M_{1/\mu,\, ij}^{(FE)} = \int_{\Omega} \frac{1}{\mu} \vec{w}_i^{(2)} \bullet \vec{w}_j^{(2)} dV , \tag{25b}$$

where the curl matrices of the grids and an additional mass matrix for the magnetic quantities have been applied. We can now even identify an implicitly defined dual grid in the FD mesh [23]. Thus, the FE discretization can be expressed within the general FIT framework, where now the material operators (FE: mass matrices) have been derived using the Galerkin approach.

A first important consequence of this result is that we now have a theoretical basis to use the FE and FIT (or FDTD) coefficients simultaneously in the same computational mesh. This is used, e.g., in [28] to implement a simulation method for hybrid grids and to analyze its properties by either the FDTD or the FE theories. It can even be proven that for Cartesian grids, the equations that arise become exactly identical when the FE mass matrices are reduced to diagonal form by a *mass lumping* process (which is mainly based on special quadrature formulas). Unfortunately, this result is not valid for other grid types.

2.5.2 Differential Forms

The strong relations between FIT and FE become even more obvious if Maxwell's theory is not described by vector quantities (as is common in most engineering textbooks), but by the mathematical concept of *differential forms*. To try a physical motivation, we start with the empirical result that, for example, the electric field strength can only be observed (and measured!) in terms of its cumulated (integrated) effect over lines in space. Following this idea, differential forms (here, of dimension $l = 1$) can be used to describe these fields by defining a map from (infinitesimally small) lines to scalar values. Physically, these values are the *electromotive force*, measured in volts. In a similar manner, we can also use differential forms with the dimensions $l = 0, 2, 3$ to describe (in classic language) potentials, fluxes, and charges, respectively.

If we transform this continuous idea into the discrete world of a computational grid, we can easily identify the grid voltages ($l = 1$) and grid fluxes ($l = 2$) of the FIT. As integral state variables, they also define a map of grid objects – now with finite size – to scalar numbers. Similarly, the *Whitney* elements of an FE discretization can obviously be interpreted as *discrete differential forms*. In this context, the material operators (mass matrices), the central concept of the discretization process, are often denoted as *discrete Hodge operators* [23, 29].

This mathematical approach and the new interpretation of the edge-element FE have made important contributions to the better understanding of the geometrical structures behind the FE discretizations. However, the impact on the development of the FIT has to be estimated as being considerably smaller, since the mapping of grid objects to scalar values has ever been a basic concept of the FIT theory. Thus, we will not give more details here, but refer to the growing number of publications on differential forms in computational electromagnetics, e.g., in [23, 30, 31, 32].

2.5.3 Extended Relations

Some of the authors' work, related to the analogies between the FIT and FE approaches, will only be briefly sketched here. In [33], we used edge elements for Cartesian grids, but (extending the results of [28]) also for dual grid quantities. The resulting hybrid discretization scheme can be shown to be consistent, and it coincides with the standard FIT after performing a *mass lumping* step.

The opposite direction was taken in [34] for triangular meshes in two dimensions: FE-type basis functions (edge elements) were used as interpolating functions within the FIT concept, in order to approximate the electric field within single cells from the scalar voltages, $\widehat{e}_j$, defined on their boundaries. This approximation can be used to compute the unknown flux quantity on the dual facet, which leads to a new scheme to build the entries of the material matrix by the direct integration formula

$$\widehat{\widehat{d}}_i = \int_{\tilde{A}_i} \varepsilon \vec{E} \bullet d\vec{A} = \int_{\tilde{A}_i} \varepsilon \sum_j \widehat{e}_j \vec{w}_j^{(1)} \bullet d\vec{A} \qquad (26)$$

$$= \sum_j \widehat{e}_j \underbrace{\int_{\tilde{A}_i} \varepsilon \vec{w}_j^{(1)} \bullet d\vec{A}}_{M^{(W)}_{\varepsilon,ij}} .$$

We obtain a purely geometrically motivated material matrix, $\mathbf{M}_{\varepsilon}^{(W)}$, for the FIT, based on *Whitney* edge elements.

The further analysis of this approach in [34] showed that this matrix only becomes symmetric (guaranteeing a stable scheme in time domain) if an additional degree of freedom in the construction of the dual mesh is used: Its vertices must be defined by a special *symmetry point* in each triangle. Since a similar derivation for the magnetic material matrix leads to the same formula for the dual point, we finally obtain a consistent and stable overall scheme. Compared to the classic approach for triangular grids in the FIT in [13] (which required an orthogonal dual grid), we can now allow considerably larger angles in the primary grid.

However, from these results a general and important disadvantage of the usage of *Whitney* elements also becomes obvious. Since the electric field is the primary quantity for these basis functions, we always obtain the permittivity matrix, $\mathbf{M}_{\varepsilon}$, (instead of its inverse) as a sparse but non-diagonal matrix. Also, since the basis functions of neighboring edges are generally not mutually orthogonal, this matrix is never diagonal. The inverse operator, which is needed for high-frequency simulations, as discussed above, is only available after a (costly) matrix inversion, or in an implicit manner by solving a linear system of equations in each time (or iteration) step. Thus, all such schemes show a considerably lower efficiency compared to classic FIT schemes with diagonal operators. In spite of the intensive research on this area, a diagonalization of the FE mass matrix for general grids so far has not been achieved [35].

2.5.4 Cell Method

The so-called *Cell Method* (CM) is based on the theoretical work of E. Tonti [4, 36], and has recently been realized as a practical implementation in [37].

Similar to the FIT, the CM also uses integral state variables – which are referred to as *global variables* – and the incidence matrices of the grid to model the geometry of Maxwell's equations. The main difference from the FIT approach (except for some differences in the notation) again lies in the derivation of the material operators. In the CM, the derivations of the material operations are based on piecewise-constant basis functions (in the sense of the FE) within the cells, and are computed in a purely geometrical manner. Thus, the CM takes an intermediate place between the FIT and FE concepts, and it can be interpreted as a variant of either of these methods. A detailed comparison of all three methods can be found in [38, 39, 40].

The CM approach of using piecewise-constant basis functions has also been used to derive an alternative material operator for the FIT in [39, 41], with similar efficiency and accuracy properties as the corresponding FE implementation on the same grid. As an important theoretical result of this work, a general criterion for the consistency of these material operators has been formulated. Surprisingly, in the case of the wave equation, different implementations of the operators lead to exactly the same system matrices, as long as they fulfill this criterion [41]. Obviously, a number of what are at first sight quite different approaches for building the discrete matrices finally coincide.

3. Conformal Modeling

3.1 Problem Description

As a main result of the theoretical analysis in the previous section, we have shown that the properties of the material operators dominate the efficiency and accuracy of the discretization schemes: The *Galerkin*-type mass matrices of the FE exist for general grids, including the important tetrahedral meshes. However, the non-diagonal permittivity matrix has to be inverted to be used in explicit time-domain schemes. This inversion is trivial for the diagonal operators of the classic FIT (and FDTD), which, however, are only available for dual-orthogonal grids. For many decades, the FDTD and classic FIT have mainly been used on simple grids such as the Cartesian grid, where they suffer from the so-called staircase error (cf. Figure 2). The geometric modeling error in the presence of oblique interfaces and boundaries dominates the overall error of the method, and reduces its second-order convergence rate to a typically non-smooth first-order behavior [24].

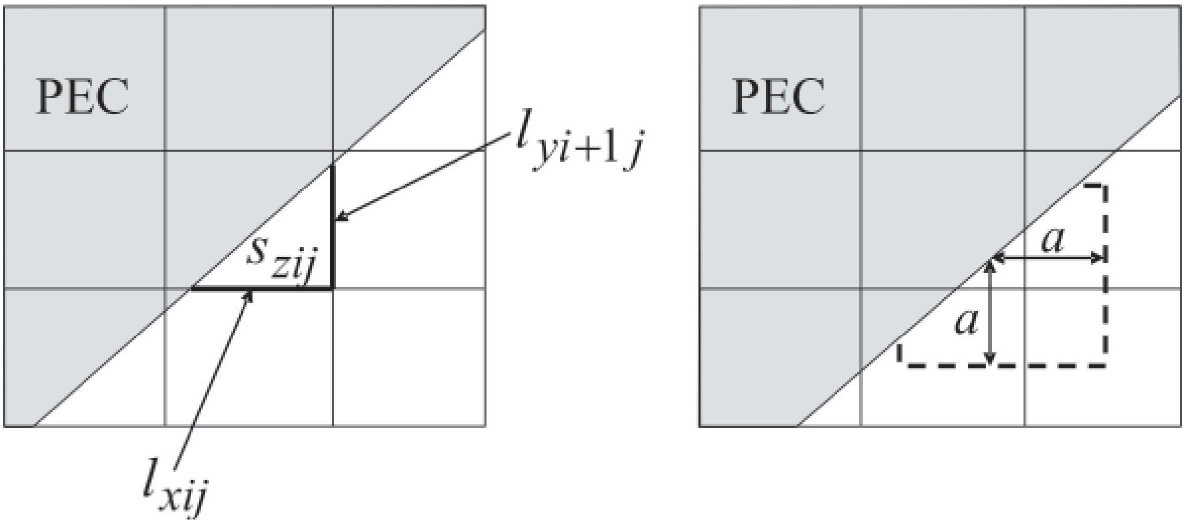

Figure 3. Conformal modeling in the FIT with the PFC scheme: In the original algorithm (a), some edges (here, $l_{x,ij}, l_{y,i+1j}$ *) and faces (here,* $s_{z,ij}$ *) are reduced at the interface. In the USC extension (b), a circulation around a virtually enlarged cell is used to keep the maximum stable time step.*

In parallel to the attempts to also find diagonal matrices for general computational meshes, so-called *conformal methods* have been proposed for Cartesian grids in the FIT [42] and FDTD [43]. They promise to realize a second-order accuracy for arbitrary interfaces to perfect electric conductors (PEC). Following [42], we refer to these methods as the *Partially Filled Cells* approach (PFC).

3.2 Basics of Conformal Modeling

The main idea behind the PFC is to allow arbitrarily shaped interfaces to a PEC *within single cells*, rather than coinciding only with their boundaries. To model these sub-cell interfaces, only the edge lengths and facet areas are adjusted in the material matrices of the classic FIT. The size of the operator stencils is not touched, and the matrices keep their diagonal form.

For simple cases, the required modifications can be easily motivated by the integral approach of the FIT, since only the metrics of local circulations have to be corrected to represent locally reduced integration areas (see Figure 3a). However, the proof of the second-order convergence in the general case is quite complicated and not fully intuitive [44].

The PFC approach can be considered to be a breakthrough in the FIT and FDTD modeling of complicated structures, since it combines the superior efficiency of diagonal material operators with the second-order accuracy of a conformal scheme, finally solving the staircase problem for PEC boundaries. Whereas the *computational logic* and efficiency of the algorithm remains untouched, we have only two slight drawbacks of the PFC. First, the computation of the matrix entries is more complicated than in the classic FIT, since it involves the processing of the geometric information about the structures. This results in an increased effort in the pre-processing phase of a simulation, which, however, is still typically cheaper than the matrix assembly in the FE. Second, the condition number of the system matrix increases, which will be discussed in more detail below.

3.3 Recent Results and Open Questions

The condition number of the system matrix is related to its maximum eigenvalue, and thus, by Equation (16), to the maximum stable time-step width in the leapfrog scheme. Due to the reduced effective size of grid edges in the PFC approach, the condition number increases and the maximum stable time step has to be adjusted accordingly. Usually this is only a minor disadvantage, which in case of need, can be solved by so-called local time steps [42].

The ability to use the "full" time step of the original (staircase) model can become mandatory when low-dispersion schemes are used, in order to minimize (or even to completely avoid) the numerical dispersion of the FIT/FDTD in one coordinate direction. A typical application is the simulation of electrically very long structures for particle accelerators [25], where, for the accurate calculation of so-called wake fields, the accumulation of the numerical dispersion error along the structure cannot be tolerated. The idea of having zero dispersion in the longitudinal direction arises from the *magic time step* of one-dimensional FDTD schemes, and can also be used in three dimensions in semi-implicit schemes [45, 46], or by recently proposed operator-splitting approaches [47].

For the combination of such schemes with conformal modeling techniques, a modification of the PFC is needed where the reduction of Δt is not required. Such an approach is the *Uniformly Stable Conformal* (USC) algorithm, proposed in [44]. Here, the reduced circulations near PEC interfaces that are responsible for the reduced stability constraint are replaced by curl operations around *virtually enlarged cells*, using interpolations of neighboring components (Figure 3b). As a result, we obtain a material operator (for the required inverse permittivity) with a small number of off-diagonal entries, where a symmetric formulation still ensures the stability of the method. The USC approach has been successfully validated and applied to a number of accelerator components in [44, 46].

A modified approach, with even simpler formulas but only slightly reduced accuracy, is the *Simplified Conformal* (SC) scheme, which has recently been proposed in [48]. Here, the reduction of edges and faces is exactly controlled and restricted to a maximum value to keep the original time step.

However, the extension of the PFC idea to dielectric and magnetic interfaces is still an open question. It has been shown [49] that simple averaging formulas such as in Equation (10), but now including the sub-cell information, would need an a-priori knowledge of the field in these cells to preserve the full accuracy of the method.

An analog of the PFC idea for the FE method has not yet been formulated. A straight-forward approach seems to comprise the difficulty of finding appropriate basis functions that also show the continuity properties of edge elements at the sub-cell interfaces. However, at least for the potential formulations of electrostatics, a mass-lumping step may be able to reproduce the PFC formulas in the material matrices of the FIT. Another promising approach with similar potential has recently been proposed in [50]; its relationship to other methods is the subject of further research.

4. Conclusions

Recent research has shown that the different paths for discretizing Maxwell's equations during the last few decades have lead to a common result, with surprising similarities among different methods. The general approach of the Finite-Integration Technique (FIT) can be seen as a natural discretization for electromagnetic field problems where the *geometry of Maxwell's equations* is transformed into the discrete space of a pair of computational grids. The FIT not only generalizes the pioneering idea of Yee's method – the separated allocation of the field components at the edges of the grid – but it is also a framework for modern Finite-Element discretizations based on lowest-order Whitney functions. All differences of these methods are now concentrated in the derivation of the discrete material operators (or mass matrices, Hodge operators, respectively.) These matrices depend on the type of the computational grid, and dominate the accuracy and flexibility of the method.

This result allows analyzing and comparing such methods with a unified methodology, and easily enables establishing hybrid methods on general (and possibly also on hybrid) grids. However, there are still some limitations of this general formulation of discrete electromagnetism. Among these are a number of important extensions, such as FE approaches with higher-order basis functions, or the conformal modeling idea of the PFC with sub-cell interfaces in the FIT.

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A Review of Laboratory Investigations of Space Plasma Waves

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Abstract

A rich variety of wave phenomena exist in virtually every region of the geospace environment. These range from simple sound waves in the neutral terrestrial atmosphere to plasma waves in the ionosphere and magnetosphere. Knowledge of the various wave signatures and driving mechanisms gives insight into the local conditions, not only at the instant that the waves are observed, but also into how the conditions may evolve in time. Comprehensive, controlled investigations of the physics associated with these waves are difficult to accomplish through in situ methods alone. Consequently, properly scaled laboratory experiments can offer a complementary approach to investigating the wave dynamics. In this work, we present a review of several key wave modes found in the various regions, with a particular emphasis on significant contributions of laboratory investigations toward the present understanding of the wave dynamics.

1. Introduction

The dynamic state of the near-Earth space environment results from the simultaneous action of a variety of forces, the combination of which never allows a true thermodynamic equilibrium to form. At best, quasi-steady-state configurations exist, generally being close to the marginal state where even a slight input of free energy can create unstable waves. As a result, the space environment is filled with waves of natural origin, as shown by even the earliest in situ probes in almost every region of space. Waves can be found in the collision-dominated neutral atmosphere, in the partially ionized ionospheric layers, and in the fully ionized magnetosphere at high altitudes.

Many factors influence the various equilibria in each region, and, in turn, alter characteristics of the waves. Among these factors are altitude, latitude, diurnal effects, ionization fraction, ion composition, spatial gradients, magnetic-field geometry, and solar-wind input. The dispersion of this complex variety of compressional, electrostatic, and electromagnetic wave modes depends sensitively on the local properties of the medium. Therefore, detailed characterizations of waves provide important clues regarding the conditions of the medium. However, far from being mere indicators of local conditions, waves play an integral role in determining the spatiotemporal evolution of the medium. Waves are often essential factors in governing energy transport, accelerating and heating particles, causing "anomalous" plasma resistivity, and in modifying particle-velocity distributions. Therefore, the study of waves is a crucial component to our overall understanding of the geospace environment.

There is a long history of experimental investigations of wave phenomena in the neutral atmosphere [e.g., 1, 2], and in the ionosphere and magnetosphere of the Earth and other planets [e.g., 3]. Such in situ measurements are critical for characterizing the dispersion properties of each region's wave modes. Accomplishing this is challenging, since there are many inherent difficulties in making in situ measurements. For example, space plasma measurements are typically made from sounding rockets or satellites traveling at approximately 1-5 km/sec, and the data yield snapshots of the medium that are highly localized in time and space. Often, when trying to interpret data from a single space vehicle, one cannot tell the difference between flying through a quasi-static spatially localized structure and a moving structure overtaking the spacecraft. Furthermore, measurements in space-based experiments are carried out in a medium that is beyond the investigator's control, and each spacecraft can carry a limited number of probes. Realistic, comprehensive views of the environment emerge only after many returns, when a statistical picture can be compiled. Even with satellites, successive passes through an interesting region are typically ~90 minutes apart, meaning that the environment could be very different on the next pass. Recently, space researchers have begun to address these fundamental issues by using multipoint measurements

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in space [e.g., 4, 5]. While multiple spacecraft can remove the space-time ambiguity from the data, such configurations do add considerable complexity and cost to the mission.

Laboratory experiments have frequently been regarded as a complementary approach to address the fundamental physics issues associated with space plasma waves. A laboratory experiment that is properly scaled to represent a particular set of space plasma conditions offers an alternative, lower-cost approach to gaining a comprehensive understanding of the essential physical characteristics of plasma-wave modes. Laboratory experiments are conducted in controlled, reproducible environments, the experiments are repeatable, and many more diagnostic techniques with high spatial and temporal resolution are available to the experimenter. The presence of a well-defined electrical ground simplifies many of the measurements. The repeatability and reproducibility of the experiments allows for the acquisition of larger volumes of data that can be much cleaner and offer a clearer picture of the observed phenomenon. A distinct advantage of laboratory experiments is their ability to thoroughly test theoretical models under wide ranges of conditions so that they can be applied with greater confidence to the space data. Consequently, laboratory experiments represent an excellent complement to in situ investigations.

In this paper, we briefly review examples of laboratory investigations of key wave modes observed in different regions of the geospace environment. We begin with a general description of the various space plasma regions, followed by a description of the basic characteristics of laboratory devices that have been used to study the details of the space plasma waves. In the discussion of geospace-relevant wave modes, we limit the scope of the paper to in situ observations of sound (neutral), gravity, Langmuir, ion-acoustic, Alfvén, ion-cyclotron, lower-hybrid, and whistler wave modes, and the corresponding laboratory experiments that have contributed to our understanding of them. Finally, we conclude by touching on some open issues for possible future laboratory investigations. Adequately covering such a broad area of plasma physics is difficult in a limited-page article. There are an overwhelming number of important contributions to the subject, ranging from theoretical investigations and numerical simulations to space- and ground-based measurements and laboratory investigations. While every attempt has been made to be as inclusive as possible in the references, some important papers have undoubtedly been missed. Such omissions are unintentional.

2. General Description of the Geospace and Laboratory Environments

The terrestrial space environment contains regions with properties that vary widely in both space and time. It is these properties that determine the spectrum of waves that each system can support. Before proceeding to describe particular wave modes, we first begin with a brief general description of the characteristics of the geospace regions under consideration. This is followed by a brief overview of some common characteristics of laboratory plasma sources used in the investigation of geophysical phenomena. The degree to which a particular laboratory device can produce scaled conditions that are relevant to space plasmas depends upon its method of plasma production and the operating parameters of the device. Thus, these are important considerations for the laboratory experimentalist.

2.1 Earth's Atmosphere, Ionosphere, and Magnetosphere

Due to the far-reaching influence of the Earth's gravitational field, the various layers of the atmosphere and ionosphere generally form concentric spherical layers and, in general, properties of each region vary with altitude above the surface of the Earth. The lowest-altitude layer, the neutral atmosphere, forms a thin layer of gas, extending from the surface of the Earth to the lowest layer of the ionosphere. Near the Earth's surface, the particle density is $\sim 2.5\times10^{19}$ cm^{-3} and it quickly falls off to approximately 10^{16} cm^{-3} at ~50 km, where the first significant levels of ionization can be detected. Important chemical, thermodynamic, and fluid-dynamical effects take place within the atmosphere, where fluid properties frequently exhibit spatial and temporal changes.

The ionosphere is a layer of partially ionized atmosphere surrounding the Earth, beginning at an altitude of ~50 km. Absorption of short-wavelength solar radiation ionizes atmospheric gas in this region during sunlit periods, and the recombination rate is low enough that significant fractions of the particles can remain ionized when in darkness. Nightside recombination does occur, however, raising the altitude of the bottom-side ionosphere. Gas dynamics and electromagnetic interactions dominate the behavior of the ionosphere, which is subdivided into three layers. The lowest-altitude ionospheric layer is the D region, located between roughly 50 km and 90 km. The E region begins at approximately 90 km and extends up to ~150 km. The F region contains the highest ionospheric plasma densities and is located between approximately 150 km and 500 km. At its peak, the F-region plasma density can exceed 10^6 cm^{-3}. Oxygen is the dominant ionospheric ion, with minority species of molecular ions at low altitudes and hydrogen ions being found in the high-altitude F region. Above ~1000 km, hydrogen is the dominant ion. Particle temperatures in the ionosphere are typically in the range 0.1 eV to 0.5 eV. Since the neutral density is still appreciable at ionospheric altitudes, collisions with neutral particle can play an important role in ionospheric dynamics.

The magnetosphere is the region of space above the ionosphere (>1000 km), but where the Earth's magnetic field is still the dominant field. In the magnetosphere, the

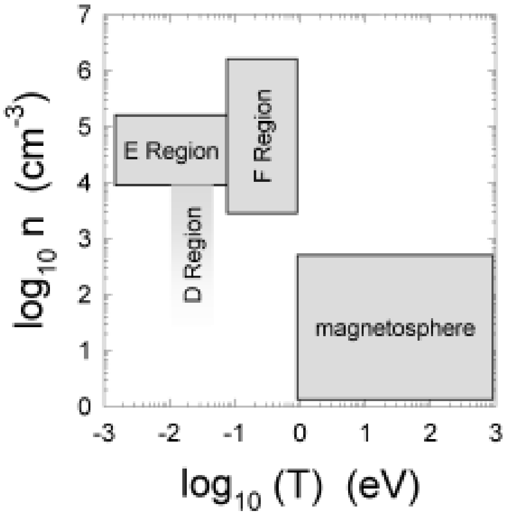

Figure 1. A schematic representation showing the approximate density and temperature regimes of various ionospheric and magnetospheric plasma regions.

density of ionized particles greatly exceeds that of the neutrals. Even so, the particle densities are still quite low, and the plasma is essentially collisionless. The magnetosphere occupies a vast region of space, reaching to $\sim 10 R_E$ on the dayside equator to several hundred R_E on the nightside equator. Here, R_E is the radius of the Earth ($= 6375$ km). The magnetosphere is populated by thermal plasma and high-energy charged particles, which originate primarily from the solar wind and the ionosphere. Hydrogen is the dominant ion species, although oxygen ions of ionospheric origin, energized by wave-particle interactions to energies large enough to escape the Earth's gravitational potential at lower altitudes, can often be found in the magnetosphere. The magnetosphere, at higher altitudes and containing high-energy particles, is not as stratified as the lower regions. Figure 1 illustrates the plasma density and temperature ranges of several regions in the near-Earth space environment.

2.2 Laboratory Plasma Devices

When considering the vast scale sizes associated with space plasmas, one realizes that it is impossible to reproduce exact space conditions in a laboratory setting. However, with careful consideration of boundary conditions and attention to matching key scaled parameters, it is possible to make laboratory experimental observations that are relevant to space physics. There have been a number of different laboratory plasma devices used to investigate space physics. When designing an experiment, it is important to consider the operating characteristics of the particular plasma device in order to make as faithful a reproduction of the essential physics of a particular space plasma phenomenon as possible. While many plasma devices have some common characteristics, each has some unique advantage for a particular operating regime. Therefore, while no one device can produce scaled conditions corresponding to all regions of space, each one has its place in the investigation of plasma oscillations.

A typical experimental device used for the study of plasma phenomena consists of a vacuum chamber, a gas supply, an ionization source, plasma diagnostics, and, in most cases, a confining magnetic field. Operation in high vacuum is necessary for several reasons. A low base pressure is desirable so that background atmospheric gases are nearly absent, or are at least reduced to insignificant levels in comparison to the gas or gases to be used for plasma production. This ensures the purity of the plasma under investigation, which is important, since correct interpretation of data often relies upon knowledge of the constituent particle masses. Reliable control of the operating pressure of the experiment is also necessary in order to maintain control of the collision frequencies among plasma electrons, ions, and neutral particles. Many different gases are used for plasma creation. The most common are helium, argon, hydrogen, and neon, although many other atomic and molecular gases have been used, including alkali metal vapors. Magnetic fields are used in laboratory devices primarily for containment of the plasma. Without a guiding magnetic field, particles would quickly be lost to the chamber walls. Magnetic-field strengths on different devices can be varied over wide ranges, from a just few gauss on large-scale space chamber experiments to several kilogauss on smaller-scale devices.

There are a number of different methods employed for ionization of the gases introduced into these chambers. Techniques used include dc glow discharges, RF discharges, microwave discharges, helicon plasma sources, oxide-coated cathode discharges, hot-filament discharges, hollow cathodes, beam-produced plasmas, and laser-produced plasmas. It is beyond the scope of this paper to describe each of these in detail, but we will focus on several of the most common sources that have been used in plasma wave investigations: hot-filament discharges, oxide-coated cathode sources, Q-machine plasmas, helicon sources, and microwave discharges.

2.2.1 Hot-Filament-Discharge Plasma Source

Hot-filament-discharge plasma sources are often used in laboratory plasma devices because of their relatively simple design, ease of operation, and wide range of operating parameters. Filament sources can generate large-area, quiescent plasmas, and are well-suited for plasma wave studies [6-8]. Tungsten filaments are ohmically heated in order to produce thermionically emitted primary electrons. The primary electrons are accelerated by an anode, and injected into a low-density background neutral gas. The accelerated primary electrons produce a steady-state plasma by the impact ionization of the neutral gas atoms. Electron emission – and, consequently, the plasma density – can be sensitively controlled by the operating temperature of the filaments. Plasma densities ranging from $10^4\ \mathrm{cm}^{-3}$ to $10^{12}\ \mathrm{cm}^{-3}$ with electron temperatures ranging from ~0.1 eV to ~3-4 eV can be produced. Ion temperatures are typically near the background temperature of the neutral gas. Since the plasma production area is limited only by the availability of power for the heating of the filaments, these sources can be used to produce large-volume plasmas, offering considerable advantages in the study of space plasmas. Typical magnetic-field strengths in devices using hot-filament discharges range from a few gauss to kilogauss levels.

2.2.2 Oxide-Coated Cathode Plasma Source

Discharge plasmas produced with oxide-coated cathode sources [9-11] have many properties that are desirable for basic space plasma research. Plasma is produced from the impact ionization between neutrals and electrons emitted from the heated cathode, which are then accelerated and injected into the low-pressure gas. These devices produce pulsed plasmas with peak densities of approximately $10^{12}\ \mathrm{cm}^{-3}$, electron temperatures of several electron volts, and ion temperatures ~1 eV. The plasmas produced have spatial uniformity, low collisions, and adjustable parameters. Similar to hot-filament plasma sources, oxide-coated cathodes can be built with large scale sizes, which is beneficial in the simulation of space-relevant phenomena. Magnetic-field strengths associated with these devices typically range from a few tens of gauss to several kilogauss. A detailed discussion of the construction and use of large oxide-coated cathodes has been given by Leneman et al. [12].

2.2.3 Q-Machine Plasma Source

The Q-machine [13, 14] is a device used primarily for studies of waves and instabilities in fully ionized plasmas. The device was originally developed in the early 1960s [13] in order to study instabilities relevant to fusion plasmas. The name of the device reflected the goal for the plasma produced to be "quiescent," or free from low-frequency instabilities, and the device is well-suited for the study of many basic low-frequency plasma waves and instabilities. The Q-machine plasma source consists of a "hot plate:" usually, a tungsten disk with a diameter of a few centimeters, which is heated to incandescence (~2300 K) by electron bombardment from a filament located behind the plate. The hot plate thermionically emits electrons with a temperature of ~0.2 eV. Plasma ions are produced by the contact ionization of an alkali-metal vapor directed onto the hot plate. Since the ions come into thermal equilibrium with the ionizing plate, Q-machines produce plasmas with equal electron and ion temperatures. Typical plasma density ranges from $10^8\ \mathrm{cm}^{-3}$ to $10^{10}\ \mathrm{cm}^{-3}$.

2.2.4 Helicon Plasma Source

Helicon plasma sources produce steady-state, high-density plasmas [15, 16]. The source derives its name from its use of helicon waves, which are bounded whistler-mode waves that are very efficient at producing plasma. Helicon plasma sources differ from other RF discharge sources in that the antenna-wave coupling leads to efficient energy deposition, allowing electrons to be heated at greater distances from the antenna [17]. Typical helicon discharges operate with 0.1-2 kW of RF input power, and produce plasmas with density up to $\sim 10^{13}\ \mathrm{cm}^{-3}$ and electron temperatures of ~2-3 eV. These sources are useful for the study of waves and instabilities [e.g., 18], particularly those associated with ion-temperature anisotropies, since the ratio of $T_{i\parallel}/T_{i\perp}$ can be controlled by the magnetic-field strength in the plasma source region [19].

2.2.5 Microwave-Discharge Plasma Source

A number of different designs for plasma sources have been based upon ionization using microwaves, or inductively or capacitively coupled RF power. One of the most common techniques for producing high-density discharge plasmas is the electron-cyclotron-resonance plasma source [17]. In this source, the strength of an axial magnetic field is chosen such that the electron-cyclotron frequency, $\omega_{ce} = 2\pi f_{ce} = eB/m_e$, matches the frequency of the input RF/microwave power. The typical microwave frequency used in such a source is 2.45 GHz, so the resonant magnetic field is approximately 875 G. A similar design has been used to develop a large cavity microwave plasma source to provide a range of space-plasma-like conditions in the Naval Research Laboratory Space Physics Simulation Chamber [20]. The source features a hard-anodized aluminum cavity, with independent tuning stubs to tune the cavity's resonant frequency to match the 2.45 GHz magnetron. The microwave power is coupled in through a waveguide and neutral gas is fed into the cavity, where it is ionized by the microwaves. A number of small outlet holes placed around the surface of a cover plate allow plasma to diffuse outward along the direction of a background axial magnetic field. The diameter of the plasma can be controlled by surrounding the plasma-production region with an axial-pinch magnetic field. The plasma density can be controlled in the range from $10^4\ \mathrm{cm}^{-3}$ to $10^9\ \mathrm{cm}^{-3}$, with electron temperatures ranging from ~0.5 to 2.0 eV, and ion temperatures near the temperature of the neutral gas.

3. Wave Modes in the Geospace Environment

Waves are a system's natural response to applied perturbations, and are the mechanism by which such disturbances are propagated through the medium. Fourier analysis allows any periodic disturbance to be decomposed into a superposition of sinusoidal oscillations with different frequencies and wavelengths. There are many possible wave modes in the geospace environment and, in particular, plasmas in magnetic fields can support a rich variety of electromagnetic and electrostatic waves. While there are many possible modes, the waves generated in a system are subject to constraints. Each mode must be a solution of the appropriate dispersion relation describing the system, which, in turn, is a function of the properties of the medium. In the geospace environment, those parameters incorporate wide ranges of densities, temperatures, and constituent species of the neutral atmosphere and of the various ionized layers in the ionosphere and magnetosphere. Gravity, the magnetic field, electric fields, collisions, spatial gradients, and particle drifts are but a few of the important characteristics of the system that shape the various dispersion relations.

For this discussion, in general, oscillating quantities associated with waves will be denoted as $\vec{\xi}(\vec{x},t)=\vec{\xi}_0(\vec{k},\omega)e^{i(\vec{k}\bullet\vec{x}-\omega t)}$, where ω is the angular frequency (rad/s), and $\vec{k}\equiv 2\pi/\lambda$ is the wave vector (m^{-1}) that defines the wavelength and direction of propagation. This representation leads to important quantities such as the wave phase velocity, $\mathrm{v}_p \equiv \omega/k$, which is the velocity with which a point of constant phase moves through the medium, and the group velocity, $\mathrm{v}_g \equiv \partial\omega/\partial k$, which is the velocity of energy flow within the wave. The phase velocity is always parallel to the wave vector, but often times the group velocity is not. We can also define an index of refraction, $\eta \equiv c/\mathrm{v}_p = ck/\omega$, which describes the dispersive properties of the wave.

3.1 Waves in the Neutral Atmosphere

To lowest order, in the vertical direction the neutral density varies as $e^{-h/H}$, where h is the altitude and H is the scale height of the atmosphere. We first encounter significant degrees of ionization at altitudes of ~50 km. However, the neutral density is still dominant, and it isn't until one reaches an altitude of approximately 150 km that the ion-cyclotron frequency, $\Omega_{ci} = eB/m_i$, exceeds the ion-neutral collision frequency. Here, *mi* is the ion mass. Therefore, neutral effects are very important at low ionospheric altitudes because plasma motion and motion in the neutral atmosphere are intimately coupled.

Near the surface of the Earth, the ionization fraction, n_e/n_n (where n_e is the free-electron density and n_n is the neutral density), is vanishingly small. Here, the gas is highly collisional, and the neutral hydrodynamic-wave modes, called acoustic or sound waves, dominate. Sound waves are longitudinal oscillations that propagate radially outward from the source of a disturbance, and are the mechanism by which acoustic sounds are transmitted. The dispersion relation for such a wave is given by $\omega = kc_s$, where c_s is the sound speed (m/s).

When the effects of gravity and altitude variation are included in the analysis, the dispersion relation becomes [21]

$$\omega^4 - \omega^2 c_s^2 k_\perp^2 + (\gamma - 1) g^2 k_\perp^2 = i\gamma g \omega^2 k_z + \omega^2 c_s^2 k_z^2 ,$$

where $k_\perp$ and k_z are the components of the wave vector transverse to and parallel to the vertical direction, and γ is the ratio of specific heats at constant pressure and constant volume. In the absence of gravity, the dispersion relation reduces to the familiar form for sound waves. When gravity is included, oscillations called gravity waves are found. For these modes, the solution indicates a complex wave vector, representing a wave that grows with increasing height [21, 22]. Therefore, gravity waves are important, since relatively inconsequential perturbations at low atmospheric altitudes grow to significant amplitudes at E- or F-region altitudes [23]. At these altitudes, where significant levels of ionization are found, drag forces on ions created by collisions with neutral particles can couple the motions of the two species. Therefore, gravity waves can be significant to ionospheric physics because of their ability to organize the plasma into periodic layers of density enhancements and rarefactions with wavelengths similar to that of the gravity wave [24]. This coupling occurs through the neutral winds driven by the pressure gradients in the gravity wave [25]. The stratification of the plasma can seed instabilities, such as the Rayleigh-Taylor instability [26], enabling plasma modes to grow. Thus, small-scale perturbations in the lower atmosphere can ultimately result in large-scale ionospheric perturbations. Such ionospheric irregularities are important because they can influence transionospheric radiowave propagation, affecting the performance and reliability of satellite-to-satellite and ground-to-satellite communications, power-distribution grids, and navigation systems.

When these perturbations are detected with ground-based instruments, such as an ionosonde, the resulting echo appears to "spread" out in frequency or altitude range due to numerous reflection paths available in the turbulent layer. In the equatorial regions, this has come to be known as equatorial spread-F, a spectacular reshaping of the lower ionosphere after sunset. Wide ranges of time scales (seconds to hours) and length scales (centimeters to tens of kilometers) characterize the various plasma instabilities that contribute to equatorial spread-F. Theoretical descriptions of equatorial spread-F have been developed. For a more complete description of the causes and effects of equatorial spread-F, see [21], or the review article by Hocke and Schlegel [27].

3.2 Plasma Waves

Gravity waves and neutral winds are only two examples of perturbation sources seeding waves in low-altitude space plasmas. Periodic phenomena can develop in space plasmas for a myriad of reasons. Even the thermal motions of the charged particles themselves can cause local currents and charge separations to arise, resulting in the appearance of perturbation electric and magnetic fields. These perturbations can ripple through the plasma, propagating as waves. External perturbations and forces can act on the plasma as well, and the waves that they trigger can be detected in many different frequency ranges. In fact, one of the most interesting and compelling features of plasma physics is the large number of wave modes that the plasma can support. However, because the waves must be solutions to the appropriate plasma-dispersion relation, the wave spectrum is often discrete, rather than a continuum.

The various wave modes depend upon the properties of the plasma, which can be described in terms of plasma parameters such as density, temperature, collisionality, spatial gradients, etc. Natural frequencies of the plasma are particularly important to the description of plasma waves. Frequencies such as the electron and ion plasma frequencies and gyrofrequencies, the upper and lower hybrid frequencies, and the collision frequencies contribute to the classification of various plasma modes and to the determination of damping, cutoffs, and resonances. Unfortunately, during the parallel development of the fields of basic plasma physics and space plasma physics, the nomenclature of the various plasma modes has become somewhat confusing, and a particular mode may often go by more than one name.

To begin the review of laboratory investigations of key space plasma waves, we begin with the simplest approximation of the system. We consider the possible wave modes in an unmagnetized, quasi-neutral, fluid plasma. This type of plasma can support two general classes of wave modes: electrostatic waves due to internal oscillations of the plasma; and electromagnetic waves similar to those that propagate in vacuum, but modified by the dielectric properties of the plasma. In their pioneering work on arc discharges, Tonks and Langmuir [28] identified two different electrostatic wave motions in such a plasma, one associated with electron motion and the other with ion motion.

3.2.1 Langmuir waves

Early laboratory investigations, in which a cold electron beam was passed through a plasma, demonstrated that the beam-velocity distribution widens, although the average beam energy remains the same [29, 30]. The experimental results could not be explained by collisional effects, and it was speculated that electric fields associated with high-frequency electron-density fluctuations could account for the beam scattering. The simplest type of electrostatic oscillation is the so-called plasma oscillation [e.g., 31, 32]. If electrons in a uniform, homogeneous plasma are displaced from their equilibrium position with respect to a neutralizing background of ions, an electric field will quickly arise to draw them back toward their original position. However, as the electrons are accelerated back, their momentum causes them to overshoot their original location, recreating the restoring electric field force on the opposite side of the partner ion. This process repeats in periodic fashion at a characteristic frequency called the electron plasma frequency,

$$\omega_{pe} \equiv \left(n_e e^2 / \varepsilon_0 m_e \right)^{1/2},$$

where e is the electron charge, m_e is the electron's mass, and ε_0 is the permittivity of free space. These oscillations are high frequency, since the process involves the motion of electrons while the ions maintain a uniform, fixed background. In a cold plasma, i.e., $T_e = T_i = 0$, the oscillations would occur at this frequency alone. A plasma in which the thermal motions of the particles are small in comparison with the oscillation amplitudes would also be considered cold in this sense. When electron thermal motion is not negligible, dispersive effects are introduced, and waves propagate through the plasma. These traveling electrostatic waves are called Langmuir waves (or are occasionally called electron plasma waves), and their dispersion relation is given by

$$\omega^2 = \omega_{pe}^2 + \gamma k^2 \mathrm{v}_{te}^2,$$

where $\mathrm{v}_{te} = \sqrt{k_B T_e / m_e}$ is the electron thermal speed, and k_B is Boltzmann's constant. If $k << \lambda_D^{-1}$, where $\lambda_D \equiv \left(\varepsilon_0 k_B T_e / n e^2 \right)^{1/2}$ is the Debye shielding length, the waves will not be Landau damped by the interaction with resonant electrons [33]. The value of γ depends upon the state of the plasma [34]. If the plasma can be treated as isothermal, then $\gamma = 1$. If the collision frequency is sufficiently high and an adiabatic equation of state is appropriate, $\gamma = 5/3$. However, in space plasmas most often the collision frequency is very low and the value of γ is 3. This description of Langmuir waves is called the Bohm-Gross equation [31], after the investigators who provided the first detailed explanation of the excitation and propagation of the waves. Langmuir waves are longitudinal oscillations, meaning that the wave electric field is parallel to the wave vector. The Langmuir-wave dispersion relation is shown in Figure 2. While the wave phase velocity can exceed the speed of light, c, for long wavelengths, the Langmuir-wave group velocity never exceeds $\gamma^{1/2} v_{te}$.

In space, Langmuir waves have been found in many different regions, including the Earth's ionosphere [35, 36], foreshock [37], the cusp [38], the heliosphere [39], in the solar wind [40], and in other planetary environments [e.g., 41, 42]. There have been numerous laboratory investigations of these waves as well [e.g., 43-48]. These waves are often generated by electron beams in both space and laboratory plasmas. For example, the Freja satellite has detected many examples of Langmuir emissions generated by super-thermal electron beams in the topside polar ionosphere [49]. The laboratory work demonstrates that when a cold electron beam travels through a plasma, velocity modulation causes the beam electrons to become bunched.

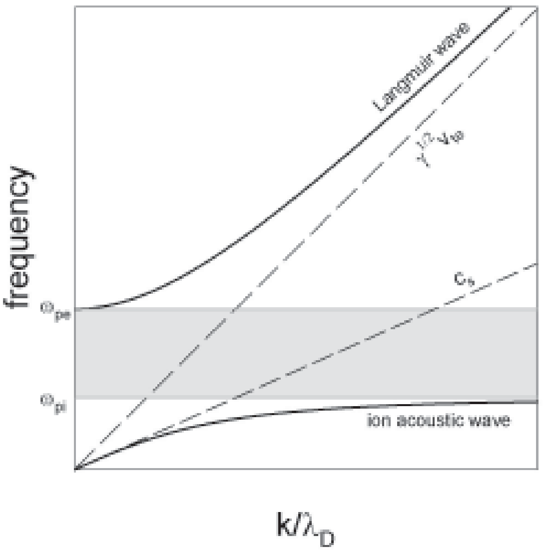

Figure 2. The dispersion relations for the Langmuir and ion acoustic waves.

The instability of an electron beam in a plasma can be used as a diagnostic [50, 51]. This method takes advantage of the fact that the frequency of most unstable waves in the spectrum of Langmuir turbulence is given by

$$\omega = \omega_{pe}\left[1-\frac{1}{2}\left(\frac{n_{beam}}{2n_e}\right)^{1/3}+\cdots\right].$$

Therefore, if the beam electron density is sufficiently small, the oscillation frequency is a very good approximation of the plasma frequency, allowing the electron density to be accurately measured. This technique has been applied in both ionospheric [50] and laboratory [51] plasmas.

When driven to the nonlinear state, it has been shown that the instability of Langmuir waves can lead to the formation of quasi-stationary soliton structures [33]. Such nonlinear Langmuir solitons may be responsible for generating at least some space observations of solitary, unipolar potential structures moving rapidly along magnetic-field lines. The spacecraft diagnostics typically detect these structures as bipolar electric field pulses [52, 53] in the auroral zone [54], the polar magnetosphere [55], the magnetotail [56], and in the foreshock region [57]. In the auroral zone, these solitary structures are found in the downward-current regions, where the electrons have been accelerated to velocities well in excess of their thermal speed [54, 58]. Observations made with the Polar spacecraft indicate that the polarity of the detected electric field is always the same, and that the scale size of the structure is related to its amplitude. The nonlinear evolution of the waves and the formation of solitons have been observed in the laboratory, as well [59-61]. These laboratory investigations show many of the same features as the space observations.

3.2.2 Ion Acoustic Waves

Tonks and Langmuir [28] also reported a second electrostatic mode in unmagnetized plasmas that is associated with ion motion These modes have frequencies so much lower than that of Langmuir waves that the ions can no longer be considered too massive to respond to the fluctuations. Rather, in this limiting case, electron inertia may be ignored, and the electrons can be expected to respond as a Boltzmann fluid, allowing for a balance between the pressure of the electron gas and the electric forces. Substituting the linearized Boltzmann equation into the ion equation of motion yields a solution for ion acoustic waves [32, 62, 63], $\omega(k)=kc_s$, where $c_s \equiv \sqrt{\gamma k_B\left(T_e+T_i\right)/m_i}$ is the ion acoustic speed. These waves are called acoustic waves because they have a linear dispersion relation similar to sound waves in neutral gas. At higher wave frequencies, the assumption of quasi-neutrality that goes into the simple derivation of the ion acoustic wave dispersion relation begins to break down, and Poisson's equation must be used. In that case, the dispersion relation is modified to read [62]

$$\omega(k)=\left(\frac{k^2c_s^2}{1+k^2c_s^2/\omega_{pi}^2}\right)^{1/2},$$

where $\omega_{pi} \equiv \left(n_e e^2/\varepsilon_0 m_i\right)^{1/2}$ is the ion plasma frequency. This dispersion relation indicates that the acoustic character of the waves exists for long-wavelength modes, where the group velocity and phase velocity are equal to c_s, as illustrated by the lower dashed line with a slope equal to the ion acoustic speed in Figure 2. At much shorter wavelengths, approaching the plasma Debye length, the character of the waves changes, and the frequency becomes independent of the wavelength. This is also illustrated in Figure 2, which shows that for large k (i.e., short wavelengths), the frequency of the ion acoustic waves asymptotically approaches the ion plasma frequency.

Since the first experimental observation of ion acoustic waves [64], laboratory plasmas have been instrumental in the characterization of ion acoustic waves, and in the validation of key theoretical predictions regarding their stability and kinetic effects. For example, theory indicates that ion acoustic waves should be significantly affected by ion Landau damping [32, 65], and, in a homogeneous plasma, the waves would typically be unstable only if there is a particle drift of sufficient magnitude. The critical electron-drift velocity depends upon the ratio of the electron-to-ion temperature. In typical ionospheric conditions, $T_e \approx T_i$, and the critical electron-drift velocity is near the electron thermal velocity [65], so that large electron currents are required for instability. Magnetic-field-aligned currents of this magnitude are not typically found in ionospheric plasmas, but they can exist in areas like the E-region auroral electrojet during strongly driven conditions [66]. If $T_e \gg T_i$,

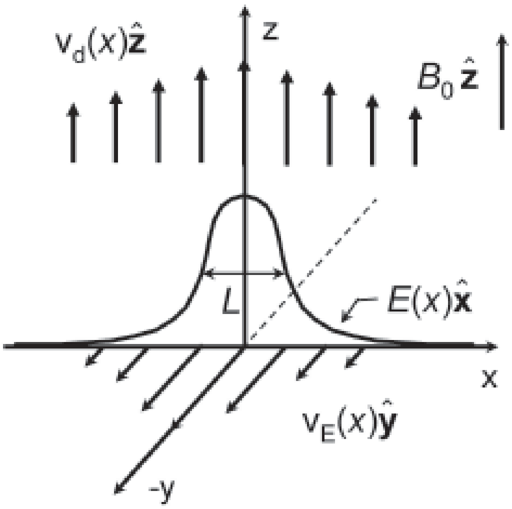

Figure 3. A schematic representation of inhomogeneous field-aligned and cross-field plasma flows. The magnetic field is uniform and is in the z direction. A spatially localized electric field points in the x direction, creating a sheared $\mathbf{E}\times\mathbf{B}$ *drift in the* $-y$ *direction. The field-aligned current also has a gradient (with different scale length) transverse to B. Reproduced by permission of American Geophysical Union from [83]. Copyright 1994 American Geophysical Union.*

the critical electron drift is relaxed somewhat to $v_{D\,crit} \approx 4v_{ti}$ [65]. Consequently, one would only expect to see unstable ion acoustic waves in regions where $T_e \gg T_i$, or in the presence of very large particle currents. Laboratory experiments, such as the Q-machine experiment of Wong, Motley, and D'Angelo [67], the discharge-tube experiments of Alexeff and Neidigh [68, 69], and the discharge plasma experiments of Gekelman and Stenzel [70] and Stenzel and Gekelman [71], have demonstrated many of these important excitation, propagation, Landau damping, and saturation characteristics of the waves. Laboratory experiments have also been used to investigate the propagation and damping of ion acoustic waves in negative-ion plasmas [72] and dusty plasmas [73], and in dust acoustic waves [74, 75].

The fact that laboratory experiments have convincingly demonstrated the theoretical predictions of strong ion Landau damping of ion acoustic waves has been key to leading researchers to look deeply for driving mechanisms in cases where ion acoustic turbulence is observed in space. For example, ion acoustic wave activity is often observed by incoherent-scatter radar facilities, such as EISCAT and Millstone Hill, during times of particle precipitation [76-78]. In situ ionospheric observations of ion acoustic waves have been made in precipitation regions with the Freja satellite [79]. While particle precipitation may account for the waves in these cases, ion acoustic turbulence is also almost always detected in the solar wind [80], although the mechanism driving the turbulence has not been definitively established. In the solar-wind plasma, mechanisms such as ion beams and electron heat conduction [81] have been considered as possibly driving the turbulence, but they cannot account for the consistent presence of the waves [80]. To try to explain how such turbulence could be generated, researchers have sought to improve the theoretical description of the plasma by including more realistic details, such as inhomogeneity of the plasma [82, 83]. Here, again, laboratory experiments have been essential in validating theoretical predictions so that they can be applied with confidence to space plasmas.

Simple ion acoustic waves change character once a magnetic field is introduced because wave-vector components and particle flows in the directions along and across the magnetic field become important. Using a general kinetic model developed by Ganguli et al. [83], which includes inhomogeneous flows both along and across the magnetic field, Ganguli et al. [84] and Gavrishchaka et al. [85] showed that the instability threshold for ion acoustic turbulence is significantly lowered by sheared magnetic-field-aligned particle flows [85]. Figure 3 is an illustration of the geometry considered in this general formalism, which includes flow inhomogeneity both along and across the magnetic field. Sheared parallel ion flow helps to make the plasma more unstable to the ion acoustic waves, by shifting the wave phase velocity out of the strongly ion-Landau damping regime. The dispersion relation for such shear-modified ion acoustic waves is given by [85]

$$\omega \approx k_{\|} c_s \sqrt{1 - \frac{k_{\perp} v_d'}{k_{\|}\Omega_i}} ,$$

where $k_{\|}$ | and $k_{\perp}$ are the components of the wave vector along and across the magnetic field, respectively; $v_d' \equiv \partial v_{i\|} / \partial x$ is the transverse gradient in the parallel ion flow; and $\Omega_i = eB/m_i$ is the ion gyrofrequency. D'Angelo [86] showed that for $\left(1 - k_{\perp} v_d' / k_{\|}\Omega_i\right) < 0$, there is a purely growing mode with $\mathrm{Re}(\omega) = 0$. For $\left(1 - k_{\perp} v_d' / k_{\|}\Omega_i\right) > 0$, the real frequency of this mode retains the character of the ion acoustic wave, with real frequency $\omega \approx k_{\|} c_s$, but, as shown in Figure 4, Gavrishchaka et al. [85] demonstrated that the shear in the parallel flow can dramatically reduce the threshold current requirement for onset of ion acoustic waves.

The effects of transverse inhomogeneities in parallel ion drifts on plasma stability were investigated in the laboratory by D'Angelo and von Goeler [87] in a double-ended Q-machine. In that study, radial (i.e., transverse) shear in magnetic-field-aligned ion drifts was produced in

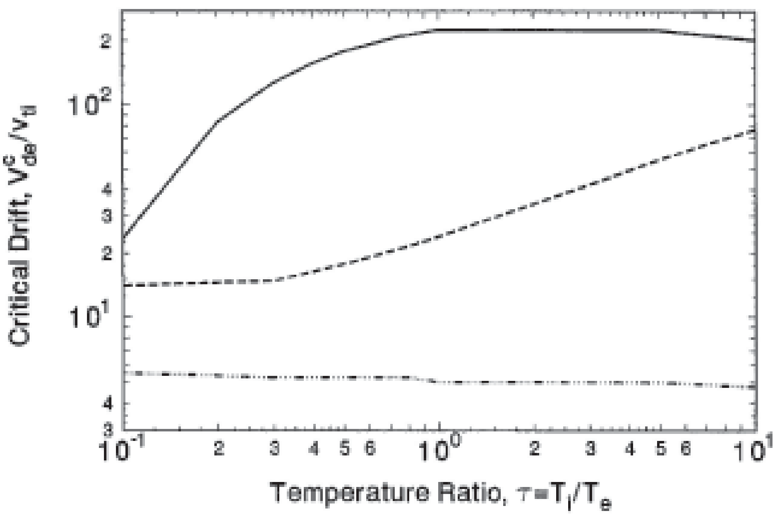

Figure 4. The temperature-ratio dependence of the critical electron drift velocity for current-driven ion acoustic waves (solid line), current-driven electrostatic ion cyclotron waves (dashed line), and for the shear-modified ion acoustic mode (dash-dotted line). Reprinted with permission from [85]. Copyright 1998 by the American Physical Society.

several different ways, using cylindrical and disk electrodes. The experiments showed that for sufficiently large shear in the flow, low-frequency oscillations could be excited. The observed mode frequency ranged from 1 to 4 kHz, well below the ion cyclotron frequency, which ranged from 45 to 170 kHz. The waves propagated primarily in the azimuthal direction, with the peak mode amplitudes in the regions of largest shear. These oscillations were described by the authors as Kelvin-Helmholtz waves, even though they are driven by shear in the parallel rather than perpendicular flow. The experimental results were found to agree well with the theoretical predictions of D'Angelo [86], and subsequently this mode has come to be called the "D'Angelo mode," in order to distinguish it from a number of other shear-driven modes.

Using a double-ended Q-machine, in which shear in parallel ion flow was produced through control of the axial magnetic-field profile, Willig et al. [88] reproduced many of the features originally observed by D'Angelo and von Goeler [87]. The results of Willig et al. [88] conclusively showed that the instability is driven by shear in the ion flow, and not the flow itself. The experiments were extended to collisional plasmas [89], and it was found that the instability was suppressed for collision frequencies exceeding ~ $v'_d/4$. Under these conditions, the wave frequency and the ion-neutral collision frequency were roughly equal. Although the experimental conditions could not exactly reproduce low-level E- or F-region conditions, these results implied that for sufficiently strongly sheared parallel flows, the D'Angelo mode can withstand the collisional dissipation and may be excited at lower ionospheric altitudes.

Q-machine experiments, performed at the University of Iowa, demonstrated the effect of shear in the parallel ion flow on the value of the critical current required for the onset of ion acoustic waves [90]. In that experiment, the value of v'_d could be controlled. Recall that in a Q-machine plasma, $T_e = T_i$, which implies a high magnetic-field-aligned current threshold for ion acoustic waves. With $v'_d \approx 0$, the magnetic-field-aligned current in the device was not high enough to excite the ion acoustic mode.

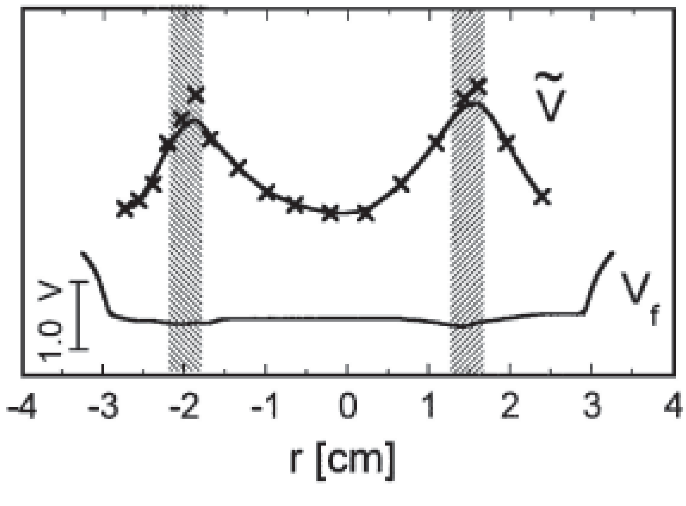

Figure 5. Radial profiles of floating potential, V_f, and wave amplitude, V. The shaded areas indicate the location of the shear layers Reprinted with permission from [90]. Copyright 2001 by the American Physical Society.

However, when the gradient in the ion flow was introduced, low-frequency oscillations were observed in the shear layer, as illustrated in Figure 5 (from Agrimson et al. [90]). The wave-propagation characteristics were found to be consistent with the theoretical predictions [85]. However, most important to the interpretation of space data was the experimental finding that the measured electron drift velocity was approximately two orders of magnitude below the threshold drift required for the onset of ion acoustic waves in a homogeneous plasma. Similar results were reported by Teodorescu et al. [91] in a later Q-machine experiment. In that experiment, laser-induced fluorescence [92] measurements of the ion distribution function were used to directly observe the shear in the parallel ion flow. The wave-propagation characteristics were again found to be consistent with those predicted by the theoretical model.

Since many space plasmas contain anisotropy in the ion temperature (i.e., $T_{i\perp} \neq T_{i\|}$), the theory was extended to incorporate these effects [93]. That work showed that the real frequency and maximum growth rate increases with increasing $T_{i\perp}/T_{i\|}$. The wave propagation angle also depends on this temperature ratio. A reinvestigation [94] of the experimental results of Teodorescu et al. [91] in light of the expanded theoretical model showed that both parallel-flow shear and ion-temperature anisotropy were necessary to account for the growth of the waves under the experimental conditions. In a subsequent experiment, Teodorescu et al. [95] used measurements of the parallel ion-velocity distribution to further quantify the effects of ion-temperature anisotropy on the shear-modified ion acoustic waves.

Sheared parallel flows are not uncommon in the space environment [96]. For example, the FAST satellite has made a number of high-resolution measurements showing magnetic-field-aligned structures with narrow spatial extent transverse to the magnetic field. In quiet geomagnetic conditions, Elphic et al. [97] found that small-scale FAC [field-aligned current] structures (~30 km width at an altitude of ~4000 km) were associated with downward currents found near the edges of inverted-V regions of electric potential. McFadden et al. [98] reported FAST observations of kilometer-scale ion beams in the auroral acceleration region. Using high-resolution measurements of ion distributions, the authors found that the magnetic-field-aligned ion beam-like flows can be very narrow, with widths of only several kilometers at an altitude of 4000 km, and with very steep transverse gradients in ion beam energy. The theory [85] indicates that when long parallel wavelengths are available, such as in space plasmas, very little shear in the parallel flow is needed to give rise to ion acoustic waves. Consequently, Kintner et al. [99, 100] have considered the shear-modified ion-acoustic instability as a possible mechanism for explaining these low-frequency waves in the ionosphere where the ion and electron temperatures are comparable. Therefore, observations such as those made with FAST raise the possibility of shear-modified ion acoustic turbulence being observed in the ionosphere.

It should be noted that in the FAST observations of localized ion flows, the entire ion population is found to flow, as opposed to an ion-beam population (n_{ib}) flowing in the background of stationary thermal ions (n_{ith}). This is the equilibrium relevant to the theory and the laboratory experiments discussed above. Theoretical analysis [101] indicates that an inhomogeneous ion beam in the background of stationary thermal ions can also display similar properties for sufficiently large ratios of n_{ib}/n_{ith}. However, laboratory experiments in this regime have not yet been performed.

To this point, gradients in plasma density have been considered negligible, due to the ionospheric applications being considered. However, in the magnetosphere, regions such as boundary layers can include both density gradients and inhomogeneous plasma flows. Kaneko et al. [102] have investigated the combination of magnetic-field-aligned ion flow shear with a plasma-density gradient. These conditions were created using a novel combination of three concentric ionizer plate sections in a Q-machine plasma source [103, 104]. Using this setup, the relative magnitude of the ion-flow shear could be controlled by the bias applied to the segmented plasma source. For sufficiently large flow shears, drift waves were observed within the regions of density and flow inhomogeneity. The wave amplitude was observed to increase with increasing shear up to a point, and then further increases led to the suppression of the instability. By considering the effects of the density gradient in the generalized kinetic treatment for the instability growth rate [83], the authors found that above the threshold value of flow shear, the growth rate increased due to reduced ion Landau damping of the waves. Further increases in the level of shear lead first to saturation of the growth rate, and then to stabilization of the waves due to a reduction in the inverse electron Landau damping in the reference frame of the flowing ions. These experiments helped to demonstrate not only the destabilizing influence of plasma flow shear, but also its stabilizing nature, as well.

3.2.3 Alfvén Waves

A plasma is considered to be magnetized when the background magnetic field, B, is sufficiently strong to alter the trajectories of the plasma species. The magnetic field influences the motion of charged particles with velocity components transverse to the magnetic-field direction through the Lorentz force, $F_M = q\vec{v} \times \vec{B}$. Under the influence of the Lorentz force, charged particles gyrate about the magnetic-field lines in the plane perpendicular to the field, while the component of their velocity along the direction of the field is not influenced by its presence. The particles gyrate in the diamagnetic direction, i.e., electrons and negatively charged particles gyrate in the right-hand sense with respect to B, while positively charged ions gyrate in the left-hand sense. The magnetic field serves to introduce several new time and length scales into the plasma: the electron cyclotron frequency, $\omega_{ce} = 2\pi f_{ce} = eB/m_e$; the ion cyclotron frequency, $\Omega_{ci} = 2\pi f_{ci} = eB/m_i$; the electron gyroradius, $\rho_e \equiv \mathrm{v}_{te}/\omega_{ce}$; and the ion gyroradius,

$\rho_i \equiv v_{ti}/\Omega_{ci}$. In order to be magnetized, the scale size of the plasma must be large compared to the particle gyroradii. One of the main effects of having a magnetic field is that the plasma is no longer isotropic, but responds in different ways to forces that are parallel or perpendicular to *B*. The anisotropy introduced by the magnetic field adds complexity to the wave modes possible in the plasma, as we saw in the previous section. Some modes are modified by the presence of the field, but other modes exist only in magnetized plasmas.

While in the previous section the effect of a background magnetic field was considered, the perturbation to this field was ignored. This is possible in a plasma with low β, where β is the ratio of the particle pressure to the magnetic-field pressure $\left(\beta \equiv 2\mu_0 n k_B T / B^2\right)$. However, if β is not negligible, then magnetic-field fluctuations become important and give rise to electromagnetic waves. In a magnetized plasma, low-frequency perturbations ($\omega \ll \Omega_{ci}$) can propagate in several ways. At such low frequencies, the plasma and magnetic-field lines oscillate together, and the plasma is said to be "frozen in" [32]. The magnetic-field lines act as strings, with mass density $(m_i + m_e)n$, held under tension, so perturbations to the magnetic field propagate in a fashion similar to waves on a stretched string. These electromagnetic waves are called Alfvén waves, and they propagate at a constant phase velocity called the Alfvén speed, $v_A = B/\sqrt{\mu_0 (m_i + m_e) n}$, where μ_0 is the permeability of free space. The mode is named after Hannes Alfvén, who first predicted that an electrically conducting fluid in a magnetic field can propagate "electromagnetic-hydrodynamic waves" [105]. Alfvén suggested that such waves may be important in solar physics, particularly in understanding sunspots. In highly magnetized plasmas, Alfvén waves play a key role in the propagation of plasma currents.

For low-frequency oscillations (i.e., $\omega < \Omega_{ci}$), two distinct Alfvén wave types exist [106]: one that is incompressible, which is typically called the "shear" Alfvén wave, and one that is compressible, typically called the magnetosonic wave. The dispersion relation for the shear Alfvén wave, derived from an MHD description of the plasma, is $\omega = k_{\|} v_A$. The shear wave is highly anisotropic, with the phase velocity directed along the magnetic field and equal to the Alfvén speed, v_A. For the compressional mode, the MHD dispersion relation is slightly modified, with $\omega = k v_A$. At low frequencies, the compressional Alfvén wave is isotropic, characterized by both magnetic-field and plasma-density fluctuations, and propagation with a phase velocity v_A at all angles with respect to *B*.

Alfvén waves are ubiquitous in space plasmas and have been found in a wide variety of regions [107], including the sun [108], the solar wind [109], the ionosphere [110], the magnetosphere [111], and the plasma-sheet boundary layer [112]. These modes represent the main method by which information about fluctuating currents or changes in the magnetic field is communicated between different regions of a plasma. As detailed in the review paper by Gekelman [113], Alfvén waves are believed to play various important roles in space, such as in the creation of parallel electric fields in the auroral regions, and in accelerating particles over large distances in interstellar space. Consequently, a number of laboratory Alfvén-wave studies have been performed [113]. Alfvén waves have even been utilized in fusion devices for plasma heating [114], either by electron Landau damping of shear Alfvén modes launched into Tokamak plasmas, or by ion cyclotron resonant heating [106].

The first direct evidence of Alfvén waves in the ionosphere was obtained from data from the Argus high-altitude nuclear tests, conducted in August and September 1958. Berthold, Harris, and Hope [115] reported detection of waves generated by the explosion, traveling at the Alfvén speed. Early in situ observations of naturally occurring Alfvén waves were reported from magnetometer data from the Pioneer [116, 117] and Explorer satellites [118-120]. In the magnetosphere, Alfvén waves are believed to be generated near regions where magnetic reconnection occurs [121]. (Magnetic reconnection is discussed further in Section 3.3.)

Laboratory observation of Alfvén waves is difficult due to their low frequency and long wavelengths. Even at higher frequencies approaching the ion gyrofrequency, the parallel wavelength of the mode is given by $\lambda_{\|} = 2\pi\sqrt{m_i/\mu_0 e^2 n}$, making the mode difficult to fit in typical laboratory devices unless the density is very high. Nevertheless, laboratory experiments have been instrumental in developing the current understanding of the physics of Alfvén waves. The first laboratory observations of Alfvén waves were made in liquid-metal experiments. In 1949, Lundquist [122] reported observations of the waves in mercury and liquid sodium, and found approximate agreement with Alfvén's wave velocity predictions. The metal was placed in a cylindrical stainless steel container, and a 1.3 T axial magnetic field was applied. The waves were driven as small torsional oscillations about the magnetic-field direction. Further evidence of the existence of the waves came from other liquid-sodium experiments [123, 124]. Early laboratory observations of the waves in plasma were made beginning in the 1950s [125, 126]. Bostick and Levine [127] observed the waves in the afterglow of a helium discharge plasma, demonstrating the necessity of a background magnetic field for the detection of the waves, and that the measured wave phase velocity was in agreement with the Alfvén velocity. Experiments on a cylindrical column of hydrogen plasma also confirmed many of the predicted properties of the shear Alfvén mode [128, 129]. Excellent agreement was also found between the experimental observations reported by Jeffcoat and Stocker [130] and Wood's theoretical predictions of bounded Alfvén waves [131].

In the early 1960s, Sugiura [132, 133] argued that geomagnetic pulsations could be interpreted as evidence for Alfvén waves in the ionosphere. Geomagnetic pulsations are fluctuations in the Earth's magnetic field observed at the surface, ranging in frequency from a few millihertz to a few hertz. This type of oscillation was observed as early as 1741 by Celsius, who correlated compass measurements with pulsations in the aurora [134]. The frequency band that the geomagnetic pulsations fall within has been subdivided into five intervals for continuous pulsations, Pc1-Pc5, and into two categories for irregular pulsations, Pi1 and Pi2 [63]. These pulsations are frequently observed on the ground as well as in space, and there have been a number of papers addressing coordinated ground-based and in situ measurements [e.g., 135, 136].

Standing Alfvén waves excited along geomagnetic field lines can form field-line resonances when the wavelength, $\lambda_{||}$,| is such that $k_{||} = n\pi/L$, where n is an integer and L is the length of the field line. This condition also leads to discrete resonant frequencies $\omega = n\pi \mathrm{v}_A/L$ [137]. For example, nightside auroral Pc5 pulsations quantized at 0.9, 1.3, 1.95, 2.6, and 3.3 mHz have been interpreted as field-line resonances excited by compressional modes [138, 139]. These resonances are seen as quasi-monochromatic oscillations in the Doppler velocities of irregularities in the F region of the high-latitude ionosphere measured by ground-based radars, and show pronounced peaks in their latitudinal power distribution. [138]. The data showed that precipitating energetic electrons were modulated at the frequency of the field-line resonance [139].

Details of Alfvén-wave field-line resonances have been studied in the laboratory. One of the first such experiments was performed in an arc-jet plasma [140] with a strong gradient in the radial plasma density. The plasma column was surrounded by external magnetic field coils spaced at half-wavelength intervals and driven 180° out of phase from each other to launch Alfvén modes. Using this setup, Tsushima et al. [141] found that the peak amplitude of the wave magnetic field could be found at radial locations in the plasma where the wave frequency satisfied the resonance condition $\omega = k_{||} \mathrm{v}_A(r)\left(1-\omega^2/\Omega_{ci}^2\right)^{1/2}$. This condition was satisfied only at certain radial locations, since $\mathrm{v}_A(r) \propto 1/n^{1/2}$. These observations were consistent with the expected conditions for Alfvén-wave resonance when kinetic effects due to the finite ion gyroradius were important. UCLA LAPD [Large Plasma Device] experiments have illustrated the properties of Alfvén-wave resonances in a warm, linear, cylindrical, helium plasma column [142, 143]. In those experiments, a sine-wave burst modulated the current drawn by a cylindrical antenna inserted into the plasma. All three magnetic-field components were measured by a three-axis magnetic-loop antenna, located downstream of the transmitting antenna. The received signals were measured for a number of different background magnetic-field strengths, while the frequency of the driving impulse was kept at half the ion cyclotron frequency. Fourier analysis of the data demonstrated that a number of standing eigenmodes existed in the shear Alfvén frequency range. As shown in Figure 6, excellent agreement was found

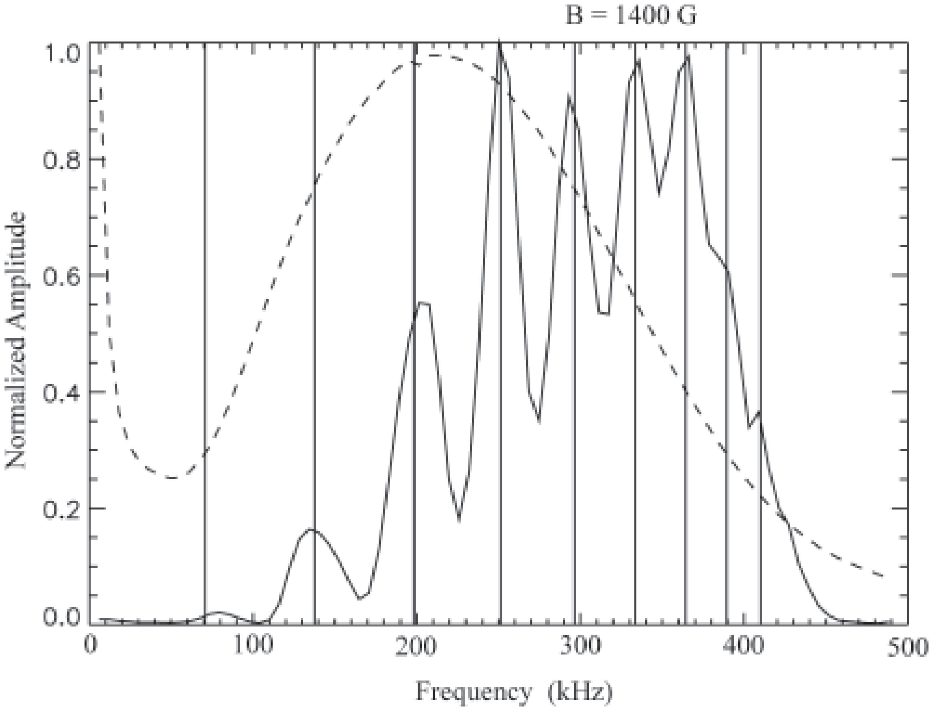

Figure 6. Laboratory observations of shear Alfvén wave resonances. Shown are power spectra of the input signal and the measured probe response. The vertical lines indicate the theoretically predicted positions of the resonances. Reproduced by permission of American Geophysical Union from [142]. Copyright 2001 American Geophysical Union.

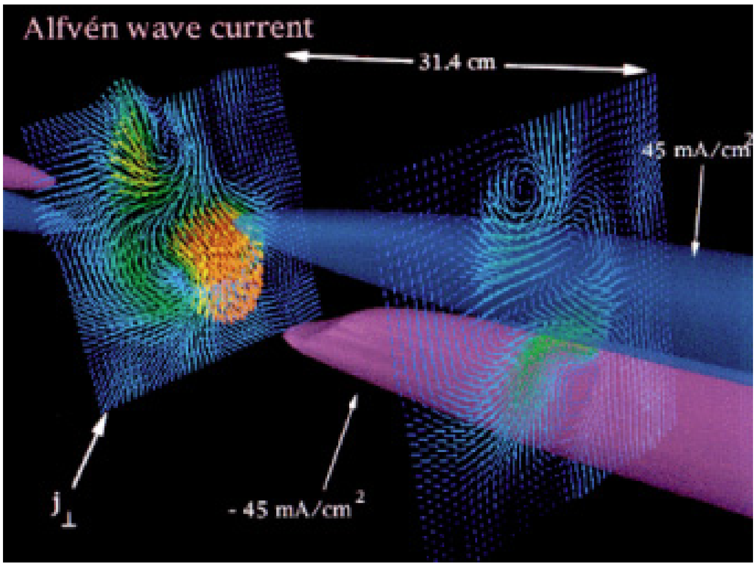

Figure 7. Laboratory measurements of the three-dimensional current associated with an Alfvén wave are shown as a representative isosurface of j_z, and vector fields of $j_\perp$. The two isosurfaces illustrate axial currents of opposite polarity that originate at the exciters. Reproduced with permission of the Institute of Physics from [160].

between the measured frequencies of the first nine harmonics of the resonant modes and the theoretically predicted values.

Perpendicular scale size is a critical parameter in determining the dispersion characteristics of Alfvén waves. For long perpendicular wavelengths, the MHD description is accurate. However, if the perpendicular wavelength of the Alfvén mode becomes comparable to the electron skin depth, c/ω_{pe}, or to the ion sound gyroradius, $\rho_s \equiv c_s/\Omega_{ci}$, the wave dispersion is modified. In the case where $\lambda_\perp \sim \rho_s$, called the kinetic Alfvén wave, the electrons can respond adiabatically to the wave electric field. In the case where $\lambda_\perp \sim c/\omega_{pe}$, electron inertia becomes important, and the Alfvén wave is said to be inertial [144]. For the kinetic Alfvén wave, $\beta \equiv 8\pi n k_B T_e/B^2 \gg m_e/m_i$ (where n is the plasma density, T_e is the electron temperature, B is the magnetic-field strength, m_e is the electron mass, and m_i is the ion mass) [142], while $\beta \ll m_e/m_i$ for the inertial Alfvén wave. A notable difference between the kinetic and inertial Alfvén waves is that the kinetic mode is forward propagating, while the inertial wave is backward propagating. This distinction may be significant in space plasmas where the trapping of dispersive Alfvén modes is considered [145, 146]. The phase-velocity reversal between the kinetic and inertial regimes [147] and mode trapping [148] have been demonstrated in the LAPD laboratory device. The inertial and kinetic regimes are also distinguished by comparison of the wave phase velocity with the electron thermal speed. In the inertial regime, the wave phase velocity is much less than the electron thermal speed, allowing the wave to interact with the bulk of the electron distribution function. The opposite is true for the kinetic case.

An experiment was performed in which a shear Alfvén wave propagated into a gradient of magnetic field, temperature, and density, which was designed to mimic an auroral field line [149]. The results showed that although the waves crossed the field lines as resonance cones, the change in perpendicular group velocity could, on average, keep the waves tied to the magnetic field. The authors concluded that the change in refractive properties as the wave moves from the kinetic to inertial regime is key to generation of Alfvén field-line resonances near the Earth.

The consequences of kinetic effects on Alfvén waves can be significant in space plasmas. For example, kinetic Alfvén waves can develop electric-field components parallel to B, which, in space plasmas, may account for the acceleration of electrons in the auroral zones [144, 150, 151]. For example, Chaston et al. [152] reported observations from the Cluster and FAST spacecraft that demonstrated the energy deposition in the auroral ionosphere by broadband ULF waves generated in the cusp and low-latitude boundary layer. By comparing the wave Poynting flux with particle energy and flux at both satellites, the authors showed that Alfvén waves are responsible for field-aligned electron acceleration, transverse ion acceleration, and Joule heating. The perpendicular wavelengths of the observed modes range from significant fractions of an L shell down to ion gyroradii and electron inertial lengths. Along the magnetic field, the wavelengths are comparable to the field-line length between the ionosphere and the equatorial plane, which can become field-line resonances when located on closed field lines. By including non-local kinetic effects, the authors could account for observed accelerated particles.

Results from LAPD Alfvén-wave experiments demonstrated the existence of the perpendicular electric field associated with Alfvén waves. Those experiments showed that when the parallel current systems associated with the wave become small, the wave propagates in a cone-like pattern, across the magnetic field. These are not like the resonance cones of Fischer and Gould [153, 154], but instead are a consequence of wave propagation (the group velocity). The short perpendicular waves also have a parallel (to **B**) electric field, which, as seen above, is believed to have tremendous importance. The ion motion was measured using LIF [laser-induced fluorescence], and the perpendicular electric field of the wave was measured recently in the LAPD experiments [155]. From these measurements, the UCLA group could infer the parallel electric field, which can cause Landau damping on electrons traveling near the wave phase velocity. This damping has been observed in an experiment by Vincena et al. [156].

Detailed LAPD laboratory measurements of the phase velocity and damping of shear Alfvén waves have been made in the intermediate regime between the kinetic and inertial limits [157]. In those experiments, the perpendicular scales were comparable to both the electron skin depth, c/ω_{pe} , and the ion sound gyroradius. The experiments demonstrated the importance of including kinetic effects in the description of Alfvén waves in a warm plasma, and also showed the effects of collisions and Landau damping on the waves.

In addition to the kinetic and inertial Alfvén-wave comparisons, wave trapping, and field-line resonance experiments, the LAPD laboratory has been the site of a number of other significant Alfvén-wave experiments with particular relevance to space plasmas. Among those results were verification of the shear Alfvén-wave dispersion relation [158], and the production of Alfvén-wave cones [159]. One of the most interesting sets of experiments performed by this group dealt with the excitation of Alfvén waves by small sources [113, 160]. Typically, these waves were excited using a semitransparent wire mesh electrode with a diameter on the order of the electron skin depth. The experiments illustrated that waves generated by small-scale fluctuating currents radiate across magnetic field lines, and are associated with complex three-dimensional current structures. This is a significant departure from the MHD model of Alfvén-wave propagation, in which the wave energy remains localized to the magnetic field lines on which the disturbance was created. The experiments also demonstrated the appearance of an electric-field component parallel to the background magnetic field. This raises the possibility of direct acceleration of particles by the Alfvén-wave electric field, similar to the acceleration seen in the in situ data. These experiments were expanded to investigate the interaction of pairs of Alfvén waves launched within the LAPD plasma column. Since the wave energy from a single source was observed to spread across the plasma column, there exists the possibility that the wave pattern from multiple small-diameter sources will interfere with each other. Figure 7 illustrates the complex three-dimensional structure in the current density arising from the interaction of two adjacent Alfvén waves. The authors noted the important consequences these results had for the interpretation of observations of Alfvén waves generated by localized sources in space. In addition to the possible existence of a parallel component to the wave electric field, the interference pattern of multiple Alfvén waves with significant transverse components can give rise to large wave amplitudes on field lines not directly tied to a source region. Structured field-aligned current systems, with transverse scale lengths of the order of the skin depth, exist in the magnetosphere.

3.2.4 Ion Cyclotron Waves

In the presence of a magnetic field, ion-acoustic-type oscillations, with k nearly perpendicular to the magnetic field, are modified by the Lorentz force. In such a case, the additional restoring force imposed by the magnetic field introduces a new resonance at the ion gyrofrequency. Electrostatic waves propagating nearly perpendicular to the magnetic field at frequencies associated with the ion gyrofrequency and its harmonics may be observed. Waves that propagate perpendicular to the background magnetic field with frequencies near the cyclotron frequency or its harmonics are called Bernstein waves [161]. Schmitt [162] studied pure ion Bernstein waves in a Q-machine plasma column by using a long wire carefully aligned along the magnetic-field direction to excite the mode. The observed waves propagated nearly perpendicular to B. Schmitt also observed Landau damping of neutralized ion Bernstein modes, which propagated with finite $k_{\|}$ and which had previously been observed [163-165]. As documented in the review article by Ono [166], much additional research was done on this mode in the late 1970s, in order to investigate characteristics of the dispersion relation, and also its potential for heating of fusion plasmas. Schmitt also investigated ion Bernstein modes associated with field-aligned flows past obstacles in magnetized plasmas, similar to flows around satellites [167]

In space plasmas, electrostatic ion cyclotron waves have been observed on numerous occasions [168-174]. These waves are usually found in association with magnetic-field-aligned currents (FAC) or up-flowing ion beams [169, 171, 174]. Such oscillations have also been detected in the optical emissions of auroral arcs [175]. Although there have been a number of space observations, clear identification of the driving mechanism for these waves has not been identified.

Laboratory experiments have been instrumental in the discovery and characterization of waves associated with the current-driven electrostatic ion cyclotron (CDEIC) instability. In a Q-machine experiment in which the diameter of a field-aligned current channel was restricted to dimensions a few ion gyroradii, D'Angelo and Motley [176] first reported observations of CDEIC waves. They found that coherent electrostatic oscillations with a frequency of $\sim 1.2\Omega_{ci}$ could be excited for parallel electron drifts with $\mathrm{v}_d > 10\mathrm{v}_{ti}$. A disk electrode, with a radius that was greater than several ion gyroradii but less than that of the plasma column, was biased to collect electron current, producing controllable levels of field-aligned current within the narrow channel [177]. A theoretical description of the wave properties, based on an infinite, homogeneous plasma, was given by Drummond and Rosenbluth [178]. The theory predicted waves propagating nearly perpendicularly to the magnetic field, with a frequency slightly above the ion cyclotron frequency, which could be driven unstably by inverse Landau damping of the drifting electron population onto the waves.

Since D'Angelo and Motley's [176] original discovery, many experimental investigations of the CDEIC instability were performed, in large part because of the expected geophysical importance of the instability. For example, Correll et al. [179] studied the growth and saturation of the instability, finding good agreement between their experimental results and theoretical predictions. The importance that the field-aligned current be confined to channels surrounded by otherwise quiescent plasma was demonstrated by Stern et al. [180], who showed that the instability is quenched unless a coherent ring of heated ions appearing periodically outside the current channel in phase with the CDEIC oscillations can form. This also highlights the fact that CDEIC waves are efficient at heating ions, which also raised the potential geophysical significance of these waves. The influence of the finite width of field-aligned current channels in the excitation of CDEIC waves was predicted by Bakshi et al. [181], and then demonstrated in the laboratory by Cartier et al. [182]. In the experiment, the magnetic-field strength decreased with axial position along the plasma column, and the disk electrode used to draw the field-aligned current could be axially translated to regions of different magnetic-field strength. Therefore, the width of the current channel relative to the size of the ion gyroradius could be controlled by the positioning of the electrode. The experiment demonstrated that the instability is "filamentally quenched" when the radius of the current channel becomes smaller than an ion gyroradius, in good agreement with the theoretical predictions [181, 183].

Rasmussen and Schrittwieser [184] provided a detailed review of the extensive research on the CDEIC instability. In general, CDEIC waves in the laboratory have been found to have a coherent narrowband spectrum ($\delta\omega/\omega_0 \sim$ few %), with a central frequency $f_0 \sim (1.1-1.2)\Omega_{ci}$ and $k_\perp \gg k_\parallel$. The critical drift required for onset of the instability in a plasma with equal electron and ion temperatures is $v_d / v_{te} \approx 0.1$. Particularly in light of the influential work of Kindel and Kennel [65], the laboratory results documenting the characteristics of CDEIC waves have been relevant to the interpretation of in situ observations of low-frequency waves found in geospace plasmas containing field-aligned currents. CDEIC waves have been observed in space plasmas [e.g., 185-189], and the waves have been considered as a possible source of transverse ion heating [e.g., 190] and anomalous resistivity [e.g., 65].

Transverse ion heating by CDEIC waves was considered to be a plausible mechanism to explain the formation of "ion conics" in the auroral ionosphere. The term "ion conic" is used to describe a conically shaped ion velocity distribution that can form when ions are heated transversely to a diverging magnetic field, such as that found in the auroral ionosphere. As the ions are heated, the originally Maxwellian velocity distribution flattens in the perpendicular (to B) direction, then "folds up," forming a cone in velocity space as the ions are accelerated up the field lines to higher altitudes by the mirror force [191]. Laboratory documentation of transverse ion heating by CDEIC waves was first given by Rynn et al. [192], followed by a number of additional experimental observations [e.g., 193-199]. These investigations typically found that significant transverse ion energization is associated with the CDEIC waves [184]. Several laboratory experiments were specifically designed to investigate the formation of ion conics. These experiments were carried out under conditions that included diverging magnetic field lines, similar to the geomagnetic field in the auroral regions. Using an electrostatic ion energy analyzer, Cartier et al. [200] found evidence for the conversion of perpendicular energy, gained from wave heating in the strong field region of a diverging magnetic field, to increased parallel ion energy in the downstream, weaker magnetic-field region. McWilliams and Koslover [201] used laser-induced fluorescence techniques, directly measuring the one-dimensional ion distribution function from a variety of angles to obtain the two-dimensional distribution function. They demonstrated the formation of conics following transverse ion heating by both CDEIC waves and lower hybrid waves. Sheehan et al. [202] also investigated ion heating and conic formation resulting from lower hybrid waves and beam-driven ion-cyclotron waves. Zintl et al. [203] demonstrated the formation of ion conics by electrostatic ion-cyclotron turbulent heating in a diverging magnetic field. In this study, the low-frequency waves were produced by the parametric decay of RF power coupled into the plasma. It was found that changes to the conic incurred when the magnetic-field profile or the level of applied RF power was changed were consistent with expectations based upon conservation of energy and adiabatic invariance.

While the laboratory investigations showed that CDEIC waves can provide transverse ion energization, features of the plasma environment in which in situ observations of low-frequency waves are made, and even characteristics of the waves themselves, are often found to be at odds with the Kindel and Kennel [65] scenario for wave generation. For instance, due to the resonant nature of the instability, the CDEIC spectrum is expected to be narrowband, with spectral features separated by the ion gyrofrequency. This is in good agreement with the laboratory observations, but often does not describe the broadband spectral features observed in the ionosphere. However, Doppler broadening caused by the large spacecraft velocity could obscure these spectra. CDEIC waves may also be problematic in accounting for the observed levels of energization in the ionosphere, since the growth rate of the instability decreases as T_i increases with respect to T_e [204]. However, perhaps the most important discrepancy with the model is that the values of field-aligned current measured by in situ probes frequently are below the threshold value required for the CDEIC instability, even though broadband waves in the ion cyclotron frequency range are clearly observed. Additionally, the spectra of these waves often include significant power at sub-cyclotron frequencies, which again is not predicted by the model of current-driven ion cyclotron waves.

As in the case of ion acoustic waves, the answers to the outstanding issues regarding ion cyclotron wave generation in space plasmas may come from a more detailed treatment of the plasma conditions where such waves are found. In situ data often indicate a correlation between broadband wave activity in the ion cyclotron frequency range and localized quasistatic transverse electric fields [96, 205]. Data from the Freja satellite, in which intense, narrow, transverse electric fields (≈ 1 V/m) were observed in association with black aurora along with low-frequency, broadband electrostatic waves [206] were an example. Since significant field-aligned currents are lacking in these regions, localized, transverse electric fields may play an important role in wave destabilization. Ganguli et al. [82, 83, 207] and Ganguli [208] theoretically investigated the generalized plasma equilibrium, which includes effects of velocity shear generated by localized transverse electric fields, density gradients, and field-aligned currents. This study identified a new branch of plasma oscillation, called the inhomogeneous energy-density-driven (IEDD) instability, which is sustained by shear-induced inhomogeneity in the wave energy density. Application of this model to space plasmas was made by Gavrishchaka et al. [209, 210]. In a plasma with $E_\perp$ where the scale size of the spatial inhomogeneity is larger than an ion gyroradius, both ions and electrons will be magnetized within the resulting shear layer. Depending upon the local conditions, the resulting oscillations may fall in the ion cyclotron frequency range, causing the waves to be misdiagnosed as the CDEIC instability [176-178], especially when field-aligned current is present. In contrast to the CDEIC instability, the IEDD waves are predicted to have a broadband, spiky spectral signature, and to propagate predominantly in the $\mathbf{E}\times\mathbf{B}$ direction [82, 211, 212]. Consequently, effects of velocity shear in the perpendicular flow and its coupling with field-aligned current [83, 210] are increasingly being considered as important elements responsible for broadband, low-frequency turbulence in space plasmas.

Laboratory investigations have been at the forefront of demonstrating the importance of accounting for the destabilizing effects of sheared particle flows [96]. For example, D'Angelo and Motley [213] investigated low-frequency waves ($\omega \sim \Omega_{ci}$) propagating across the magnetic field near the plasma column boundary. Comparison with a theoretical model showed these observations to be consistent with ion drift waves resulting from plasma-density gradients. Kent et al. [214] later studied two types of low-frequency waves found near the edge of a Q-machine plasma column. Similar to the earlier work of D'Angelo and Motley [213], Kent et al. identified drift waves localized near the region of maximum density gradient, while the other, higher-frequency wave was confined to a region containing shear in the rotational velocity of the plasma. The frequency and localization of the waves were found to agree well with a theoretical model for the Kelvin-Helmholtz instability. Jassby and Perkins [215] extended these studies of the edge oscillations, confirming that velocity shear drove the waves at the column boundary. The mode was identified as the Kelvin-Helmholtz instability [216] by comparison with numerical integration of the radial wave equation, using experimentally measured radial electric-field and plasma-density profiles.

Jassby [217] conducted a detailed analysis of the Kelvin-Helmholtz instability, comparing theoretical results with measurements from a Q-machine experiment in which the level of transverse shear could be controlled by an externally applied radial electric field. The electric field was confined to an annular region several ion gyroradii wide and located entirely within the plasma column. Low-frequency ($\omega < 0.5\Omega_{ci}$) waves, identified with the Kelvin-Helmholtz instability, were observed within the electric-field layer, traveling in the direction of $\mathbf{E}\times\mathbf{B}$ rotation. The Kelvin-Helmholtz instability has geophysical relevance, since it can be destabilized for modest levels of shear, and, in its nonlinear phase, can steepen to locally generate stronger regions of sheared flow [83, 218]. In turn, these stronger shears can seed higher-frequency instabilities, such as ion cyclotron or lower hybrid waves, which may be important in plasma energization and transport. For very large rotational velocities, Jassby [217] also reported observations of waves with frequencies slightly above the ion gyrofrequency, having amplitude and growth rates smaller than the Kelvin-Helmholtz waves.

Some investigators have reported observations of ion cyclotron waves associated with plasma inhomogeneities in the form of three-dimensional double layers. These are boundary layers across which large differences in plasma parameters are maintained. Typically, these structures are characterized by "U"- or "V"-shaped equipotential profiles having strong, localized transverse electric fields at the perimeter, and weaker magnetic-field-aligned electric fields on the interior. The presence of similar structures in the ionosphere and magnetosphere was proposed by Mozer et al. [219], where they are believed to account in large part for the field-aligned acceleration of precipitating particles in the auroral zones. Since intense wave activity and heating are frequently found in the vicinity of these structures, their effects on plasma are of considerable interest.

The destabilization of ion cyclotron waves by strong transverse potential structures was investigated in the laboratory by Nakamura et al. [220] and Sato et al. [221]. Two plasmas of different diameters and potentials were merged, creating a strong, three-dimensional double layer, the shape of which could be controlled by adjustment of the axial magnetic-field profile. Electrostatic oscillations with frequencies slightly above the ion cyclotron frequency and its harmonics were detected in the localized region near the maximum radial potential gradient. The frequency of these waves changed with the transverse localized electric-field strength, and azimuthal propagation in the direction of $\mathbf{E}\times\mathbf{B}$ rotation was observed.

Alport et al. [222] investigated strong, three-dimensional magnetized double layers in a weakly ionized argon discharge plasma that included a diverging magnetic field. Large-amplitude, narrowband electrostatic waves, with frequencies corresponding to the ion gyrofrequency (and several harmonics) at the position of the parallel double layer, were observed. The waves were found to propagate primarily in the radial direction, transverse to the axial magnetic field. Field-aligned currents, ions and electrons accelerated by a parallel electric field, and inhomogeneous transverse electric fields were all considered as possible driving mechanisms for the waves, although clear identification could not be made. Aoyama et al. [223] later demonstrated that ion cyclotron oscillations could be induced by a strong potential structure that was controlled using a small, isolated, electron-emissive disk. A broadband peak with center frequency ~10% above the ion cyclotron frequency was observed in the oscillation spectrum when the disk potential became positive with respect to the plasma potential.

In nearly all of the experimental investigations of the CDEIC instability, small, biased disk electrodes ($r < r_{plasma}$) were used to draw field-aligned currents along the plasma column [184]. These electrodes had the effect of producing density depletions within the field-aligned current channel and strong transverse electric fields near the boundaries. In a study of the effects of the field-aligned-current-channel diameter on CDEIC mode characteristics, Alport and van Niekirk [224] and van Niekirk et al. [225] observed waves excited by these localized electric fields. In these experiments, electron current was drawn to an electrode with continuously variable diameter in a single-ended Q-machine. For diameters ranging from 1 to 10 ion gyroradii, CDEIC waves were observed in the expected fashion. However, when the disk diameter exceeded $12\rho_i$, where ρ_i is the ion gyroradius, an abrupt transition in mode characteristics was observed. This consisted of a 15% increase in mode frequency, an order-of-magnitude decrease in mode amplitude, and a transition to azimuthal propagation. It was speculated that these were shear-driven ion cyclotron waves, since some of the observed characteristics qualitatively corresponded to theoretical predictions [82].

Laboratory investigations of effects due to the combination of field-aligned currents and localized transverse electric fields have been performed in an experiment in which the relative contributions of each of these free-energy sources could be externally controlled. With no applied transverse electric field, the CDEIC instability was observed at levels of field-aligned current consistent with the earlier experiments. A controllable, transverse (radial) electric field was applied to the cylindrically plasma column. The electric field was localized within a cylindrical layer with width $\sim 2\rho_i$. This enabled the experimenters to create radially sheared transverse (azimuthal) flows localized to the edges of the $\mathbf{E}\times\mathbf{B}$ drifting cylindrical layer. Using this setup, Koepke et al. [226] and Amatucci [227] demonstrated that the character of electrostatic ion cyclotron waves can change significantly when the effects of transverse velocity shear are included. When weak (or zero) electric fields were applied, CDEIC waves were observed across the entire width of the current channel when sufficiently large parallel electron drifts were present ($\mathrm{v}_d \geq 0.1\mathrm{v}_{te}$). The characteristics of these waves were consistent with previously reported CDEIC wave experimental results. However, as the magnitude of the transverse electric field was increased, increasing the shear in the $\mathbf{E}\times\mathbf{B}$ flow, a distinct transition in mode characteristics occurred. The wave amplitude became larger than the CDEIC case, the spectrum became much broader (extending below Ω_{ci}), the waves became spatially localized within the velocity-shear region, and a transition to azimuthal propagation in the $\mathbf{E}\times\mathbf{B}$ direction was observed. The frequency of this mode depended sensitively on the magnitude of the applied electric field, and was found to downshift with increasing E. By comparison with theoretical predictions, it was determined that these waves resulted from the resonant response of the IEDD instability [226-228]. In this case, similarly to the CDEIC instability, the energy to drive the waves is provided by the magnetic-field-aligned electron drift by Landau resonance with the waves; however, the process is modified by the presence of the localized transverse electric field [209, 210]. This experiment demonstrated that the combination of field-aligned and cross-field flows is important and relevant to the interpretation of in situ data, because even small amounts of velocity shear can lead to significant modifications of the spectrum of ion cyclotron waves.

Perhaps the most relevant feature of this mode to geophysical plasmas is the fact that the threshold current for the ion cyclotron waves can decrease substantially in the presence of velocity shear. The instability condition for current-driven ion cyclotron waves requires that the electron drift velocity slightly exceed the parallel phase velocity of the waves. In the homogeneous plasma case, the parallel wave phase velocity is given simply by $\mathrm{v}_\phi = \omega / k_{\|}$. When inhomogeneous transverse plasma flows are present, a Doppler shift that cannot be transformed away must be included. Thus, the parallel phase velocity of the waves becomes $\mathrm{v}_\phi = \left(\omega - k_\perp \mathrm{v}_{\mathbf{E}\times\mathbf{B}}\right) / k_{\|}$, which lowers the critical electron drift velocity [229]. While field-aligned current still acts as the principle free-energy source, shear can cause important modifications to the resonance conditions of the plasma. The reduction in threshold field-aligned current in the presence of sheared transverse plasma flows was demonstrated by Amatucci et al. [230]. As illustrated in Figure 8, the experimentally measured threshold current

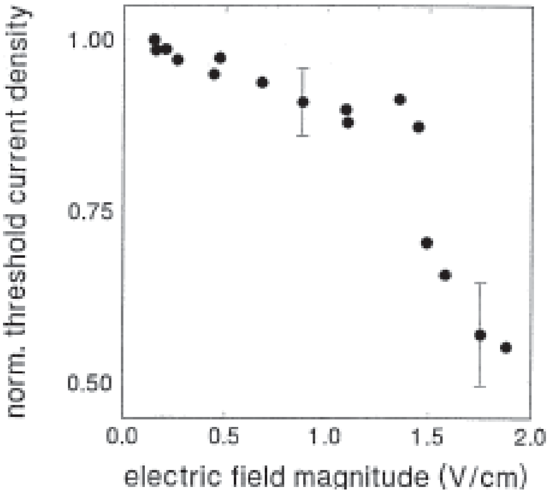

Figure 8. The experimentally measured threshold current density for ion-cyclotron waves in the presence of sheared transverse plasma flows. In this example, the threshold current was reduced by ~50% as the magnitude of the transverse shear was increased. Reproduced by permission of American Geophysical Union from [230]. Copyright 1994 American Geophysical Union.

density for ion-cyclotron waves was reduced by ~50% as the magnitude of the transverse shear was increased. This result may be significant to some in situ wave observations where the field-aligned current levels were too low to excite the CDEIC instability, such as the hydrogen cyclotron waves detected by AMICIST [205]. However, care must be taken when applying this result to space plasmas, since only discrete values of $k_\perp$ are possible in the laboratory case, while a wider range of perpendicular wavelengths are likely to be available in space [209].

In the case of even stronger shears, the threshold current density can be reduced to zero and ion cyclotron waves can grow from a reactive response of the plasma to shear-induced inhomogeneity in wave energy density [82, 208]. This regime was investigated by Amatucci et al. [231] in the Naval Research Laboratory's Space Physics Simulation Chamber (NRL SPSC). These experiments demonstrated that sufficiently strong shear can give rise to waves in the ion cyclotron frequency range without the dissipation of a field-aligned current. The experiments were performed in a plasma column containing a transverse electric field having width $\sim 2\rho_i$, created in a manner that resulted in insignificant levels of field-aligned current. This setup has similarities to black aurora, which can contain intense localized transverse electric fields and broadband, low-frequency electrostatic turbulence, even in the near absence of field-aligned current [206], and also has similarities to Freja data [232]. In the NRL experiments, with the application of sufficiently strong shear, broadband electrostatic waves in the ion cyclotron frequency range were observed, localized to the strong electric-field region (i.e., the velocity-shear region) [231, 233]. The wave propagation was predominantly in the $\mathbf{E}\times\mathbf{B}$ direction, but the axial wavenumber was observed to increase as the electric field was increased, implying that the waves became more oblique. In contrast to the resonant response of the instability, the reactively driven waves up-shifted in frequency with increasing electric field, with the spectral peak beginning below the ion cyclotron frequency near mode onset and shifting to approximately $2\Omega_{ci}$. Quantitative comparison between theory and experiment was made by extending previous slab models [208] to include effects due to the cylindrical nature of the SPSC experiment [234]. The reactive response of the IEDD instability was observed in later Q-machine experiments, as well [235].

The laboratory experiments on velocity-shear-driven ion cyclotron waves provide important observational signatures regarding the relative contributions of transverse velocity shear in wave generation. These signatures have been invoked in conjunction with ground-based photometer measurements of rapid variations in the frequency of flickering aurora [236]. The shear-driven ion cyclotron waves may be particularly relevant to space plasmas, because the broadband waves may be efficient for the initial perpendicular ion heating, leading to formation of ion conics and ion outflow. Laboratory measurements of perpendicular ion energization, resulting from the shear-driven waves in collisionless conditions, were made in the NRL SPSC [233, 237]. As shown in Figure 9, (from Walker et al. [237]), the ion temperature was observed to increase by a factor of two following onset of the shear-driven waves. In other cases, temperature increases of a factor of four were observed [233]. No increase in ion energy was detected in the presence of strong, but sub-threshold, transverse electric fields, establishing the waves as the source of ion heating. The measured heating was found to be most pronounced within the velocity-shear region [233], and the most efficient energization was observed to occur when the Doppler-shifted mode frequency, $\omega - k_\perp \mathrm{v}_{\mathbf{E}\times\mathbf{B}}$ approached a harmonic of the ion cyclotron frequency. This was in good agreement with the resonance condition for ion heating, $\left|\omega - k_\perp \mathrm{v}_{\mathbf{E}\times\mathbf{B}} - n\Omega_{ci}\right| < 2\pi\delta f$, where δf is the spectral width of the mode [238]. Since the Doppler shift is directly proportional to the magnitude of the $\mathbf{E}\times\mathbf{B}$ flow, the electric field plays an important role not only in the initial destabilization of the waves but also in determining the resonant heating conditions. The experimental results suggested that velocity-shear-driven instabilities may be a plausible explanation for ionospheric observations of broadband, low-frequency electrostatic-wave activity and associated ion heating, particularly in cases where field-aligned current is sub-critical. Additionally, since the IEDD instability maintains a large growth rate over a wide range of temperature ratios [209, 238], it represents a more efficient source of ion heating than the CDEIC instability, which is self-limiting as T_i increases with respect to T_e [204]. The experiments were extended to the collisional regime, and the studies suggested that the shear-driven ion cyclotron waves are very robust in the presence of ion-neutral collisions [239, 240].

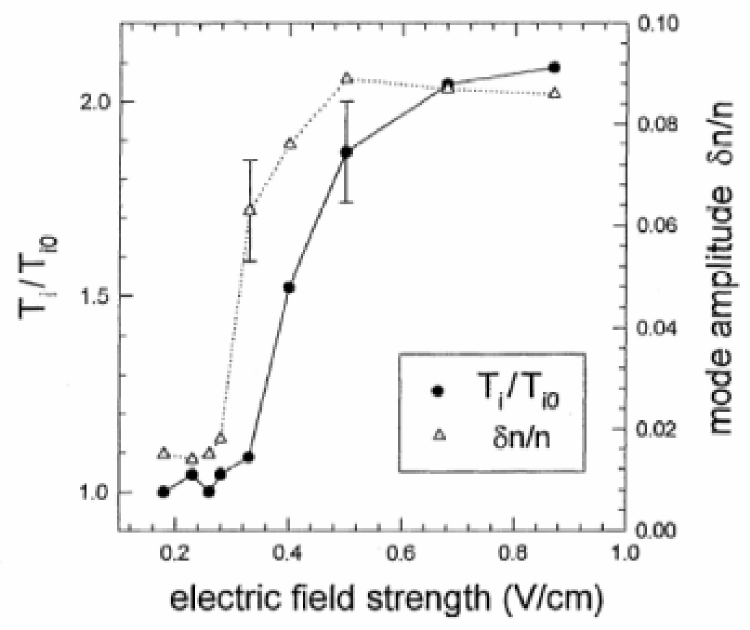

Figure 9. Laboratory measurements of perpendicular ion energization demonstrate an ion temperature (triangles) increase by a factor of two following the onset of the velocity-shear-driven ion-cyclotron waves (circles). Reproduced by permission of American Geophysical Union from [237]. Copyright 1997 American Geophysical Union.

In the low-altitude ionosphere, where highly collisional plasmas are prevalent, transverse electric fields can also lead to Joule heating of the ions [e.g., 241-243]. NRL SPSC investigations of ion energization by both the wave and Joule-heating mechanisms were carried out in plasma conditions that were representative of the low-altitude ionosphere [239, 244]. The two distinct heating mechanisms were isolated, and a transition between the regimes was observed as the ion-neutral collision frequency was increased. The experiments showed that in plasma conditions where the ion-neutral collision frequency was below the wave frequency, energy dissipation through wave-particle interactions was the dominant source of ion heating. At higher collision frequencies, where the waves were collisionally damped, the Joule-heating regime was observed. These results may have geophysical significance, since the ionospheric source region for heavy ions that are observed in the magnetosphere lies in an altitude range where there is a transition from collisional to collisionless conditions. Often, it is not clear from in situ observations just how plasma energization takes place when both wave- and Joule-heating mechanisms are possible.

By increasing the ion-neutral collision frequency beyond the point where the shear-driven ion cyclotron waves were suppressed, the experimenters observed the onset of a higher-frequency mode, with characteristics similar to those of the Farley-Buneman instability [245, 246]. In this regime, the ions are effectively unmagnetized, but the electrons continue to execute $\mathbf{E}\times\mathbf{B}$ motion, leading to the development of a cross-field current. Because of the presence of strong velocity shear, it was not entirely clear whether this mode was the classical Farley-Buneman instability or the collisional version of the electron-ion hybrid instability [247]. The experiments illustrate that shear-driven processes may play important roles even in collisional plasmas, such as the *E* region. The higher-frequency mode observed may be relevant to Type 3 and Type 4 radar echoes, which have been associated with transverse velocity shears [248].

Koepke et al. [249] observed decreases in the excitation thresholds of both the CDEIC and IEDD instabilities with increasing ion-neutral collisions. In the absence of transverse electric fields, the CDEIC instability could be excited for collision frequencies $\left(\nu_{in}/\Omega_{ci}\right) \leq 0.12$, in good agreement with previous measurements [250]. However, when a transverse electric field was included, ion cyclotron waves could be detected for ν_{in}/Ω_{ci} as large as 2.2, indicating that velocity-shear-driven ion cyclotron wave growth may be possible at very low ionospheric altitudes. In other Q-machine experiments [251], spectral features identified as velocity-shear-driven ion cyclotron waves were observed, with some features appearing at frequencies normally associated with ion acoustic waves [252].

Most of the laboratory investigations into the effects of transverse, localized electric fields have focused on the physics associated with one isolated velocity-shear layer. In the ionosphere and magnetosphere, these electric fields are often part of a broader region containing many such structures, and are frequently associated with broadband electrostatic waves [e.g., 205]. Koepke et al. [253] observed very broadband, low-frequency electrostatic waves associated with multiple electric-field structures in close proximity to each other. The frequency of these waves extended well below the ion cyclotron frequency, and the waves were observed at values of field-aligned current that were sub-critical to the CDEIC instability. The structured electric fields were produced using an end electrode consisting of a central disk surrounded by several annular rings, each of which could be biased. They found that the

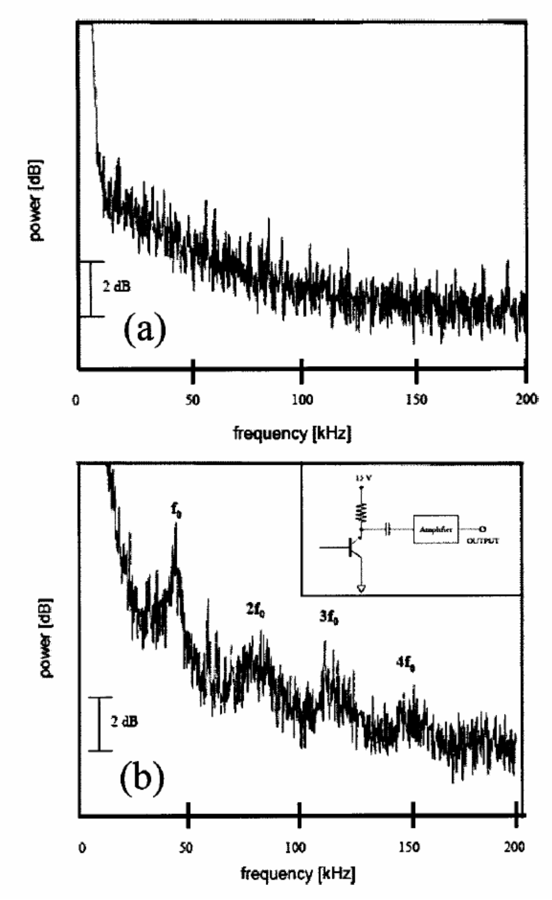

Figure 10. A laboratory observation of multiple cyclotron harmonic excitation using a broadband input signal. (a) The spectrum of the background plasma noise in the absence of ion flow shear and with no signal applied to the antenna. (b) The multiple cyclotron harmonic spectrum observed in the presence of ion flow shear when a broadband signal was applied to the antenna. The inset in (b) shows the circuit used to generate the white noise spectrum. Reprinted with permission from [259]. Copyright 2004 American Institute of Physics.

closely spaced, discrete structures together behaved effectively as one larger electric-field structure. Discrete features were also observed within the broadband spectrum, which were unambiguously identified with specific eigenvalues predicted by the theoretical model for the IEDD instability [82]. Reynolds and Ganguli [254] theoretically investigated the interaction between multiple electric-field structures. In their model, the magnitude, width, direction, and proximity of the electric field could all be controlled. It was found that structures with spatial separations greater than ~ $2\rho_i$ generally act independently, and observed wave modes will be locally determined by the characteristics of each structure. However, for separation distances less than ~ $2\rho_i$, coupling between the eigenfunctions can occur, allowing multiple discrete structures to act as a single entity.

Cross-field gradients in magnetic-field-aligned ion flow has also been shown to lead to electrostatic ion cyclotron wave growth. Ganguli et al. [84] and Gavrishchaka et al. [255] used a kinetic model to predict wave growth resulting from sufficient transverse shear in parallel ion flow, even in the complete absence of field-aligned current. Merlino [256] demonstrated the instability of parallel velocity-shear-driven ion cyclotron waves using a fluid treatment. The kinetic treatment of the problem indicates that wave growth can occur due to a shear-induced change in the sign of the ion-cyclotron damping [84]. Furthermore, the critical value of shear required for such inverse cyclotron damping is roughly independent of the cyclotron harmonic number. Consequently, growth can occur at a number of higher harmonics of the ion cyclotron frequency as well, giving these shear-driven ion cyclotron waves particular relevance in space plasmas. For example, at altitudes of approximately 4000 km, the FAST satellite has shown strong gradients in parallel ion flow in the auroral acceleration zone [96], as well as observations of spectra with discrete harmonic structure at multiples of the hydrogen cyclotron frequency [255].

The existence of this mechanism has been demonstrated in several laboratory experiments [257-259]. The experiments demonstrated that the transverse shear in parallel ion flow is destabilizing to ion cyclotron waves, and that higher harmonics are excited, as well. A key feature of the experiments performed by Kim et al. [259] was that the waves were destabilized in the absence of field-aligned electron current, verifying the prediction [84] that ion-flow shear alone can drive electrostatic ion cyclotron waves. Figure 10 shows a sample spectrum from the experiment. This example shows the simultaneous amplification of at least four harmonics of the ion-cyclotron waves launched from an antenna driven with a broadband white-noise input signal. The experimental results were also consistent with the predicted threshold shear condition $(1/\Omega_{ci})(1-n\Omega_{ci}/\omega)(k_\perp/k_\parallel)\nabla_\perp \mathrm{v}_\parallel > 1$. This threshold condition illustrates the potential impact of this mechanism for space plasmas. Given the availability of long parallel wavelengths, this condition can be satisfied for even very modest amounts of shear in the parallel ion flow, not only at the fundamental, but at higher harmonics, as well.

Once again, we note that in these experiments, the entire ion population flowed along *B*, consistent with the FAST observations. Similar results are also predicted to occur in the presence of a ion beam, provided n_{ib}/n_{ith} is sufficiently large [101], but no laboratory experiment for that configuration has yet been performed.

3.2.5 Whistler/Lower Hybrid Waves

In the frequency range well above the ion cyclotron frequency but below the lower of the plasma and electron cyclotron frequencies, the "electron" whistler/lower hybrid branch of oscillation is the dominant wave mode in space plasmas. These whistler and lower hybrid modes are a ubiquitous feature of geospace plasmas and of other planetary magnetospheres as well [e.g., 260-263]. In the simple cold-plasma approximation of electromagnetic-wave propagation along the background magnetic-field direction (i.e., $\vec{k} \parallel \vec{B}_0$), with the wave electric field oriented perpendicular to $\vec{B}_0$, two solutions to the dispersion relation exist, corresponding to right- and left-hand circularly polarized modes [32, 262]. In this frequency range, the right-hand circularly polarized mode corresponds to the parallel-propagating whistler wave. Its cold plasma dispersion relation is given by

$$\eta_R{}^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_{pe}{}^2/\omega^2}{1-\omega_{ce}/\omega},$$

where η_R is the right-hand-mode index of refraction, and ε_0 is the permittivity of free space [32]. The mode is not restricted to propagation only along B, but instead can propagate at oblique angles to the magnetic field, up to a resonance-cone angle given by $\theta = \tan^{-1}\left(k_\perp/k_\parallel\right)$ [264, 265]. Spectral components of the electron whistler mode can be found in all ranges between the electromagnetic (whistler) and electrostatic (lower hybrid) limits. Typical spectrograms of VLF hiss electric-field data from the ionosphere show that the spectrum is sharply bounded from below by the local lower hybrid resonant frequency $\omega_{LH} \equiv \left[\omega_{pi}^2\omega_{ce}^2/\left(\omega_{pe}^2+\omega_{ce}^2\right)\right]^{1/2}$. Often, the falloff in the wave electric-field power spectrum at the lower hybrid resonance is sufficiently sharp that the measured cutoff frequency can be used to estimate the local plasma density. No such boundary at the lower hybrid resonance is found in the magnetic-field spectrum, indicating the electrostatic nature of the oscillations near the low-frequency limit [261]. At the high-frequency end, the wave spectrum extends up to the smaller of the electron plasma or cyclotron frequencies. While waves along the whistler/lower hybrid branch are carried primarily by the electrons, a branch of lower-frequency oscillations, called hydromagnetic or ion whistlers, also exists at frequencies around the ion cyclotron frequency [266].

Naturally occurring whistler modes are typically initiated by broadband bursts of radio noise, released during lightning discharges. Natural occurrences of these electromagnetic signals often propagate down to the surface of the Earth, where they can be detected in the very-low-frequency (VLF) range (~1-10 kHz) [262]. Whistler waves have now been investigated for nearly a century, since Barkhausen [267] first reported observations made with long-wire antennas in 1919 [261]. As the cold plasma dispersion relation shows, the higher-frequency components of the wave travel faster than the lower-frequency components, a feature that produces the familiar falling tone of lightning-produced whistlers. Many other varieties of these waves have an almost musical quality as well, with frequencies lying within the audio range. In addition to whistlers, there are spectra that have come to be known as chorus, VLF hiss, saucer, risers, and others. (For an interesting collection of audio data from magnetospheric whistler modes and other space plasma waves, see the Web page "Sounds of the Magnetosphere," maintained by Dr. Donald Gurnett's group at the University of Iowa, at http://www-pw.physics.uiowa.edu/space-audio/index.html). The study of whistler wave phenomena is now a mature field, and whistlers have been well documented in books such as that by Helliwell [262] and review papers such as that by Al'pert [268]. Stenzel [269] provided an excellent review of the rich history of whistler observations in space and numerous related laboratory experiments.

Many of the first laboratory experiments were driven by the desire to use whistler waves and the lower hybrid resonance as a means of heating in fusion plasmas [270]. One of the earliest laboratory investigations of whistlers was made by Gallet et al. [271], who considered the possibility of using whistlers as a diagnostic of the magnetic field in a toroidal plasma. Dellis and Weaver [272] studied whistler propagation in a linear argon afterglow plasma, and showed agreement with cold-plasma theory in terms of both wave polarization and re*fractive index. Fisher and Gould* [153, 154] performed an experimental and theoretical investigation of the radiation pattern produced by a small dipole antenna in a magnetized plasma. That work provided the first experimental indication that lower hybrid waves propagate along resonance cones about the background magnetic field [264, 265]. Briggs and Parker [273] also investigated lower hybrid resonance cones by launching waves from an open-ended waveguide. Hooke and Bernabei [274] demonstrated that a plasma resonance with short perpendicular wavelength exists at frequencies near the lower hybrid resonance.

Stenzel and Gekelman [275] and Gekelman and Stenzel [276] utilized a novel circular-line-source antenna to focus resonance cones. As this ring electrode was driven, each point along the wire acted as a point source of an individual resonance cone. These cones overlapped at some distance away from the antenna, determined by the individual resonance-cone angles. The superposition of the waves created a region of maximum wave intensity away from the antenna, and thus removed boundary effects due to the antenna's structure. This arrangement was used to study a number of interesting nonlinear effects, such as the formation of density depletions within the focal region and the generation of turbulence. Resonance cones have also been used as a diagnostic for the direct measurement of plasma density in the laboratory [277].

Lower hybrid turbulence in space plasmas has become an active area of research in recent years since the discovery of what have been called lower hybrid cavities, spikelets, or lower hybrid solitary structures (LHSS) [278]. LHSS are spatially localized structures characterized by electric-field fluctuations with wave amplitudes up to approximately five times the ambient level at frequencies both above and below the local lower hybrid resonance [263]. In the ionosphere, the structures are typically characterized by density cavities of a few percent to several tens of percent. The structures appear to extend along the magnetic-field

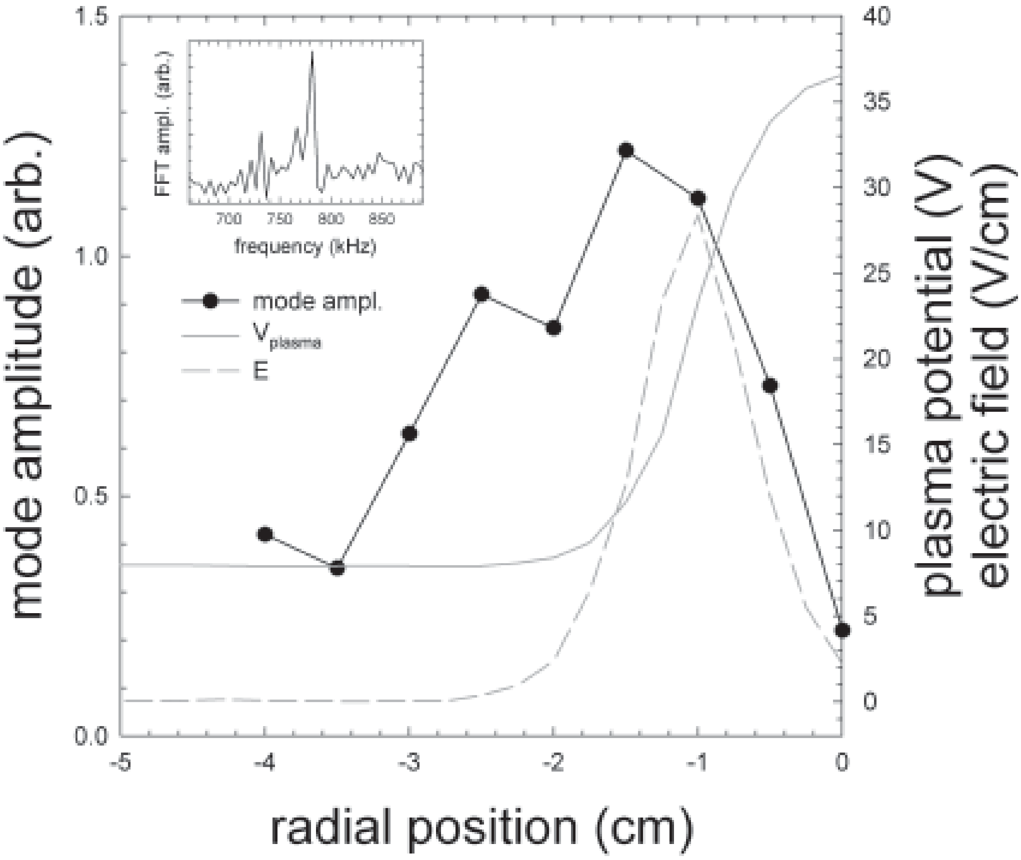

Figure 11. The laboratory excitation of lower hybrid waves by sheared transverse electron flows with scale lengths less than an ion gyroradius. The measured wave amplitude (circles) was shown to peak near the position of the localized transverse electric field (dashed line). The solid line is the measured plasma potential. For this experiment, the ion gyroradius was 3.5 cm. Reprinted with permission from [279]. Copyright 2003 American Institute of Physics.

direction over distances much greater than a kilometer, and have measured transverse widths of the order of 10-100 meters. Spatially resolved interferometer measurements of the LHSS wave electric fields show that the waves rotate in the right-handed sense for frequencies above the lower hybrid resonance, and in the left-hand sense for frequencies below it. Numerous examples of LHSS have been detected by both sounding rockets and satellites [263]. Besides being important due to the abundance with which they are found, LHSS are also relevant to issues such as magnetospheric-ionospheric coupling, since transversely heated ions are typically found collocated with LHSS. For a detailed overview of the theory, space observations, and laboratory experiments relevant to LHSS, see the review article by Schuck et al. [263].

Plasma inhomogeneities can also play an important role in the destabilization of lower hybrid turbulence. Similar to the velocity-shear-driven ion-cyclotron and ion-acoustic wave mechanisms, lower hybrid waves can be driven by sheared cross-magnetic-field electron flows in regions where the scale length of a localized electric field becomes less than an ion gyroradius [247]. These conditions can frequently be found in magnetospheric boundary layers, such as the plasma-sheet boundary layer and the magnetopause. These layers are important since they are primary regions of solar wind mass, energy, and momentum transport into the near-Earth space environment. Particularly during periods of solar activity, the boundary layers can become compressed to scale lengths less than an ion gyroradius. The theoretical predictions indicate that the plasma can react to relax these highly stressed conditions through the generation of instabilities in the lower hybrid frequency range. Laboratory experiments performed in the NRL SPSC have helped to illustrate the dynamics of such highly localized regions [279]. Transverse, localized dc electric fields, with scale lengths of approximately $0.25\rho_i$, were created using two interpenetrating plasmas in a fashion that allowed for the independent control of both plasma density gradients and electric-field strength. Using this setup, it was demonstrated that such highly localized electric fields can drive lower hybrid oscillations independent of the presence of a density gradient. Good agreement with the theoretical predictions was found, and the mechanism driving the waves was identified as the electron-ion hybrid instability [247]. Figure 11 shows that the largest wave amplitudes (symbols) were found near the localized electric-field region (dashed line). For these experiments, the ion gyroradius was approximately 3.5 cm. The experimental results lent support for a scenario of wave-induced relaxation of highly stressed magnetospheric boundary layers such as the plasma-sheet boundary layer. As solar-wind stresses cause the compression of the boundary layer, gradients in plasma parameters across the layer can lead to self-consistently generated localized electric fields and highly sheared cross-magnetic-field flows. These sheared flows, in turn, lead to plasma instabilities that act to dissipate the shear and widen the boundary layer, which is accomplished by the turbulent mixing of particles from different magnetospheric regions and cross-field transport.

The whistler-lower hybrid branch of plasma oscillation represents a continuum of waves, the character of which varies from predominantly electrostatic to predominantly electromagnetic. Schuck et al. [265] showed theoretically that lower hybrid waves, propagating in a homogeneous plasma with $\omega_{pe} \gg \omega_{ce}$, begin to demonstrate electromagnetic characteristics as the wavelength approaches the electron collisionless skin depth (approaching from short to long wavelength). Waves propagating with the critical value of $k_\perp$ where the perpendicular group velocity is zero are called Gendrin modes [280], which propagate without dispersion. These modes distinguish the electrostatic lower hybrid wave regime, where the mode is backward propagating ($k_\perp \left(\partial\omega/\partial k_\perp\right) < 0$), from the forward-propagating electromagnetic whistler mode regime ($k_\perp \left(\partial\omega/\partial k_\perp\right) > 0$). In the laboratory, Bamber et al. [281, 282] investigated conversion between the whistler and lower-hybrid modes by launching whistler waves onto a cylindrical magnetic-field-aligned density depletion. These experiments were motivated by in situ observations of mode conversion of ground-based-transmitter-launched whistlers to lower hybrid turbulence near density irregularities [283, 284]. The laboratory experiments showed that the largest-amplitude lower-hybrid waves are located on the incident side of the density depletion. Inside the density cavity, the lower-hybrid wave amplitude is very small, and there is virtually no activity on the far side of the cavity. In another series of LAPD experiments, Rosenberg and Gekelman [285-288] also investigated the interaction of a whistler wave incident on a density cavity. Unlike most in situ observations of LHSS as rotating electrostatic eigenmode structures trapped in the interior of a density cavity, the laboratory experiments showed electromagnetic waves trapped on the boundary of the density cavity. It has been argued [289] that this discrepancy with sounding-rocket observations [290] resulted from the ratio of the density-depletion diameter to the electron collisionless skin depth, D/δ_e, being 1-3 for the laboratory plasma, compared to 0.1-0.4 for ionospheric observations. Recent analysis of Freja satellite data does show that in some cases, both wave electric and magnetic fields can be enhanced on density gradients associated with irregular (asymmetric) density variations [291]. Irregular density profiles are distinct from those associated with LHSS, which statistical studies have shown to be Gaussian in shape [292, 293]. The Freja data showed the wave magnetic-field amplitude roughly doubling at the density gradients within limited frequency intervals. At the same time, the wave electric field was observed to increase by a factor of 10-20, indicating that the wave fields associated with the cavities are mainly electrostatic [291].

While there have been many important laboratory whistler and lower hybrid wave studies, those performed by Stenzel and coworkers [294-301] represented some of the most comprehensive work on whistler mode characteristics to date. Many features of whistler waves either predicted by theory or observed in space have been investigated by this group. For example, Stenzel and Gekelman [302] observed the "backward" propagation of lower-hybrid waves in a homogeneous plasma. At the same time, Gekelman and Stenzel [303] studied the filamentation instability of large-amplitude lower-hybrid resonance cones propagating in a density gradient, detecting density perturbations in regions of highly peaked RF field. Later experiments further investigated nonlinear effects due to whistlers [304]. Since plasma inhomogeneity is important to the propagation of whistlers in the space environment, both homogeneous and inhomogeneous plasmas have been studied in the laboratory. Stenzel investigated the ducting of small-amplitude whistler waves in pre-existing density depletions [305], and also the "self-ducting" of large-amplitude whistler waves [306, 307]. That work showed that small-amplitude whistler waves could be ducted within regions of plasma-density depletion for wave frequencies less than half the electron cyclotron frequency. Ducting of large-amplitude whistlers was originally believed to result from a "filamentation instability" due to the field pressure of the large amplitude pulse. The wave then propagated largely undamped in the self-consistently formed density duct. Later experiments by Sugai et al. [308] demonstrated that these density ducts formed even when the antenna was driven at a frequency for which whistler waves did not propagate. Sugai et al. concluded that electrons heated in the antenna near field led to the formation of the density duct. However, both experiments demonstrated that a fully-formed density duct guides small-amplitude whistlers virtually undamped over a broad range of frequencies [263].

In space plasmas, whistler and lower hybrid waves are often associated with energetic field-aligned electron beams, or with anisotropic electron distributions [262, 263]. Similar behavior has been observed in large laboratory devices. Stenzel [309] showed that beams can produce broadband whistler turbulence, consisting mainly of oblique waves near the resonance cone, in a large laboratory plasma. In that experiment, the parallel phase velocity was found to match the velocity of the electron beam. Furthermore, Stenzel [309] demonstrated the Cherenkov instability (inverse Landau damping) of a small-amplitude whistler pulse launched from an antenna. The data indicated the growth of the wave along the direction of the electron beam where the wave-particle resonance, $\omega = k_\parallel \mathrm{v}_{beam}$, was satisfied. Experiments such as these are relevant to the generation mechanisms of VLF hiss, and also to active experimentation in space, such as electron-beam injection.

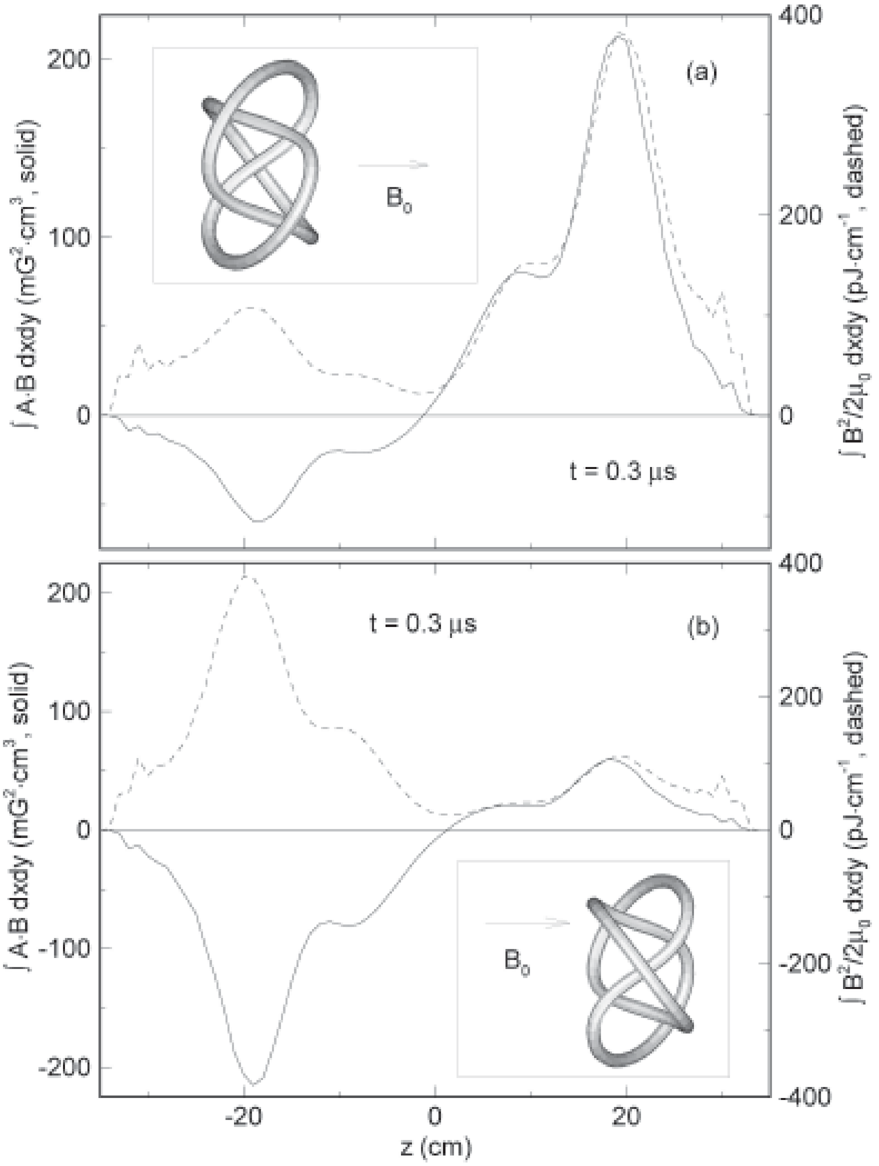

Figure 12. The experimentally measured values of helicity (solid line) and integrated wave magnetic field energy density (dashed line) for "knotted" antennas with right-handed helicity (a) and left-handed helicity (b). The experiments demonstrated the ability to launch whistler waves with preferential directionality. Reprinted with permission from [313]. Copyright 1997 by the American Physical Society.

Whistler waves may also be responsible for scattering and accelerating magnetospheric electrons to very high energy levels during storms. Horne and Thorne [310] showed that outside the plasmapause, electrons with energies up to ~60 keV can be scattered into the loss cone by these waves. They also showed how trapped electrons can be accelerated up to MeV levels. Utilizing ray-tracing techniques, the authors showed that at high latitudes, the whistlers can scatter MeV electrons into the loss cone, as well. Merideth et al. [311] investigated the acceleration of radiation-belt electrons using CRRES satellite particle and wave data. They found that the observed enhancements of relativistic electrons were consistent with a model of stochastic acceleration of electrons by Doppler-shifted cyclotron-resonant interactions with the whistler waves.

One of the most basic and important roles played by whistler waves is that of being one of the primary methods by which pulsed currents are transported in a plasma. Urrutia and Stenzel [298, 312] demonstrated the three-dimensional characteristics of current closure in a plasma where pulsed currents were drawn to electrodes. They found that the leading edge of the current propagated as the whistler mode, and the current path formed nested helices in the plasma. The also showed that large transient currents, which can exceed the electron saturation current, could be drawn to the electrode. The fact that the whistlers propagated with helicity led Rousculp and Stenzel [313] to a more-efficient antenna design for launching whistlers. As shown in Figure 12, by choosing an antenna with the proper helicity, whistler waves can be launched in a preferential direction. Such results may be important to future space-based wave-transmission and reception experiments.

3.3 Magnetic Reconnection

Magnetic reconnection is the topological rearrangement of magnetic-field lines, and is a fundamental process in determining the interaction between a plasma and a magnetic field [314, 315]. Reconnection is a key physical process for explosive events in space plasmas, such as geomagnetic substorms and solar flares. In the near-Earth space environment, a magnetic storm can arise quickly, with a duration ranging from 30 minutes to several days. The magnetic energy released in such a storm can lead to bright auroral displays, and can even hinder satellite communications. Large dissipative events such as these may result from the sudden onset of fast magnetic reconnection.

Understanding how magnetic energy can be so rapidly released in substorms and solar flares has long been a pursuit of the space physics community. The prevailing notion is that the explosive reconnection events occur in regions where the magnetic field reverses, resulting in an "x-line" configuration. Energy is released when the strongly bent magnetic-field lines spring outward. Since the magnetic field and plasma are strongly linked together, there is an outward flow of plasma from the reconnection region. Furthermore, the outflow of plasma from the x-line leaves a low-pressure region behind, into which plasma can flow from a direction perpendicular to the outflow direction. Satellite observations have illustrated this process and have shown that the escaping plasma travels at the Alfvèn speed [316]. Recently, multipoint measurements made by the Cluster spacecrafts have demonstrated the existence of drift kinetic Alfvén waves propagating outward from a reconnection x-line in the magnetopause [317]. At the same time, kilovolt O+ ions were also detected at the magnetopause. These observations are significant because they may identify magnetic reconnection as the source of many ionospheric observations of Alfvén waves, and that the Alfvén waves may provide the transverse ion energization required at ionospheric altitudes to lead to oxygen-ion outflows.

The fundamental issue to be resolved involves the rate of magnetic-energy release. The classical magnetohydrodynamic (MHD) theory of magnetic reconnection first proposed by Sweet [318] and Parker [319] predicts a rate of energy release much slower than that which is observed. The reason for this discrepancy is that the long, narrow magnetic "nozzle" formed limits the inflow of new plasma, thus limiting the outflow. Recent theoretical work has challenged the basic assumptions in the classical MHD picture of reconnection [e.g., 320-326]. That work shows that the breaking of magnetic-field lines actually takes place within very narrow regions close to the x-line. The scale length, L, of this region can be smaller than the ion inertial length, $\delta_i \equiv c/\omega_{pi}$, where c is the speed of light and ω_{pi} is the ion plasma frequency. The narrowness of the region causes the traditional MHD model of electrons and ions moving together to break down. This illustrates that Hall physics plays a critical role in the process of magnetic reconnection, since the Hall term decouples the motion of ions and electrons on scale lengths less than δ_i . Thus, the reconnection process is controlled by c/ω_{pi} rather than the electron inertial length, c/ω_{pe} . The independent motion of the two plasma species can lead to the onset of lower hybrid and whistler-wave turbulence, which can accelerate the electrons to high energies near the x-line and allow the reconnection to proceed at much higher rates.

There have been several experimental investigations of the magnetic reconnection process [315]. These experiments have probed both the ideal MHD and the non-MHD regimes. In the 1980s, in a linear-discharge plasma device at UCLA, Stenzel and Gekelman [327], Gekelman and Stenzel [328], and Gekelman and Pfister [329] investigated reconnection in the unmagnetized ion regime. A reconnection region with an x-type neutral point on axis was established by driving currents in parallel-sheet conductors. The experiments were well suited for studying the reconnection region, and issues such as neutral-sheet formation and wave excitation were investigated. Among the results reported from these experiments was the observation of "out-of-plane" components of the magnetic field near the x-line. The existence of such fields is key to the theory of whistler-wave-induced particle acceleration [330]. These out-of-plane magnetic field components have recently been observed at the magnetopause [331].

Princeton University experiments in the MRX device [332] investigated magnetic reconnection driven in the quadrupole field formed between two toroidal plasmas with annular cross sections formed around two toroidal flux cores. Among the investigations performed in this device was an experimental test of the Sweet-Parker model. In these experiments, it was shown that by assuming classical Spitzer resistivity, the Sweet-Parker model cannot explain the measured reconnection rate. However, from a detailed experimental analysis of Ohm's Law, the experimenters were able to determine that the effective resistivity of the plasma can be significantly enhanced over the classical value [333]. The larger effective resistivity, along with plasma compressibility and downstream pressure, were found to help to account for the observed reconnection rate. Local ion heating in association with the reconnection was also found [334]. Subsequent MRX experiments focused on detailed investigations of the plasma turbulence in the current sheet [335]. Strong lower hybrid turbulence was found at the current-sheet edge, which was consistent with theoretical predictions for the lower hybrid drift instability.

4. Some Open Issues for Future Laboratory Investigations

While much progress has been made to date in the laboratory investigation of space-relevant plasma waves, there remain many open issues for future investigations. For example, to better model ionospheric plasmas, experiments performed in laboratory devices capable of producing multi-species plasmas would be a benefit. The presence of ions with differing masses can have a dramatic impact on the dynamics of the plasma. The interplay of heavy and light ion species can give rise to new modes of oscillation at unexpected frequencies, such as sub-ion-cyclotron frequencies [336, 337]. There have been several previous experimental investigations performed on current-driven ion cyclotron waves in plasmas with two positively charged ion species [338, 339]. Those experiments showed that electrostatic ion cyclotron waves could be excited near each of the respective ion gyrofrequencies. However, the sub-harmonic nature of the rotation waves discussed in [336] have not yet been investigated in the laboratory. Many more experiments have been performed in multi-species plasmas containing negative ions, usually using an electron-attaching gas such as SF6 to form the negative ions.

With each new generation of space-based experiment, improvements in the temporal and spatial resolution of the instrumentation reveal new features in the natural environment. High-time-resolution measurements have uncovered interesting features such as electron phase-space holes. While such an experiment may prove difficult to set up in the laboratory due to the short time duration for an electron to traverse the plasma column, laboratory experiments would be a valuable addition to the investigation of this phenomenon.

Space experiments provide indications of the importance of Alfvén-wave parallel electric fields. Controlled laboratory experiments providing direct measurement of the parallel Alfvén-wave electric field and further studies of its consequences would be an excellent contribution.

Electron solitary holes (ESH), which have been observed in a number of different locations and conditions in space plasmas [e.g., 340], are another phenomenon deserving of renewed laboratory attention. Electron solitary holes are spatially coherent potential structures associated with quasistatic magnetic-field-aligned electric fields in space plasmas [341]. Observationally, electron solitary holes appear as single-period structures with bipolar parallel electric-field signatures [342], and spatial scale sizes on the order of the Debye length [341]. Large-amplitude electron solitary holes are often found in the auroral acceleration region in association with upward-directed electron beams [343]. Electron solitary holes were investigated in the laboratory by Saeki et al. [344] in a single-ended Q-machine, and characterized as stable electron-velocity space vortices propagating near the electron thermal velocity. Since then, relatively few laboratory investigations of this phenomena have been carried out. Since a statistical picture of the properties of in situ observations of electron solitary holes is now emerging [345], the need for further laboratory investigation of electron solitary holes properties now exists.

Laboratory experiments can also be instrumental in shedding light on new manifestations of phenomena previously investigated in the laboratory. For example, as described above, there is now a substantial body of experimental work that has been performed on the effects of parallel and transverse velocity shear on plasma stability. However, to date all of these experiments have focused on the excitation of electrostatic waves. New experiments extending the previous work into the electromagnetic regime would be quite valuable in uncovering key signatures of such waves to facilitate interpretation of space data. In particular, the study of generation mechanisms, characteristics, and plasma effects of electromagnetic ion cyclotron (EMIC) waves would be of importance to space plasmas. Electromagnetic ion cyclotron waves may play a particularly important role in ion heating in space plasmas [e.g., 346].

One remarkable revelation that is emerging from the theoretical studies of shear-driven ion-cyclotron waves [255] and confirmed by laboratory experiments [347] is that the origin of the spiky parallel electric fields, separated by ion-cyclotron times as observed by the FAST satellite, are primarily due to linear combinations of multiple cyclotron harmonics. Such phenomena are generally assumed to be intrinsically nonlinear. Other phenomena related to velocity inhomogeneity, such as lowering of instability thresholds, ion energization, and the origin of the broadband nature of spectra, although long observed in space, became clear only through laboratory simulations of these phenomena. This illustrates the importance of laboratory simulation of space phenomena.

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Call for Nominations for URSI Awards

A call for nominations for the five URSI awards will be issued to the Presidents of the URSI Member Committees, the Chairs and Vice Chairs of the URSI Commissions, and to the former laureates of the URSI awards. However, the URSI Board wants the radio-science community to know that in principle anyone can nominate a radio scientist for an URSI award, by contacting one of the above-mentioned people to whom the call for nominations will be issued. All in the radio-science community are urged to consider nominating appropriate candidates for the awards.

URSI has five awards. Details of the awards, the rules for the awards, a nomination form, and a list of past laureates of the URSI awards can be found on the URSI Web site, http://www.ursi.org, by clicking on "URSI Awards" under "Meetings" on the left-hand side. The URSI awards are presented during the opening ceremony of each General Assembly; the next awards will be presented during the XXIXth General Assembly, to be held in Chicago, Illinois, USA, August 9-16, 2008. The following is a brief summary of the URSI awards; please refer to the information on the Web site for full details

The *Balthasar van der Pol* and the *John Howard Dellinger Gold Medals* honor the memory of two scientists who were closely associated with URSI for many years. The Medals are awarded to outstanding scientists whose achievements in any of the branches of science covered by the Commissions of URSI have been particularly valuable.

The *Appleton Prize* is awarded by the Council of the Royal Society of London, and honors the memory of Sir Edward Appleton, FRS, President of URSI from 1934 to 1952. The Prize is awarded for outstanding contributions to studies in ionospheric physics.

The *Booker Gold Medal* honors the memory of Professor Henry G. Booker, who served as URSI Vice President, 1969-1975, and Honorary President until his death in 1988. The Medal is awarded for outstanding contributions to telecommunications or a related discipline of direct interest to URSI.

The *Issac Koga Gold Medal* honors the memory of a scientist who was closely associated with URSI for many years. The Medal is awarded to a Young Scientist, of age not more than 35 on September 30 of the year preceding the General Assembly of URSI, who has made an outstanding contribution to any of the branches of science covered by the Commissions of URSI.

In all cases, the awards are for career achievements of the candidate, with evidence of significant contributions within the most recent six-year period. No member of the URSI Board of Officers is eligible.

The call for nominations will go out early in March, 2007. Nominations must reach the URSI Secretariat by August 15, 2007. After reviewing the information on the URSI Web site, nominations should be made through the Presidents of the Member Committees, the Chairs and Vice Chairs of the URSI Commissions, or a former laureate of an URSI award.

Radio-Frequency Radiation Safety and Health

James C. Lin

Current Bioelectromagnetics Research Activities in Europe

The membership in the European Union (EU) will expand again when Bulgaria and Romania join the EU on January 1, 2007. Beside the historic emotions to which this may give rise, the occasion will carry great symbolism, and will have important political and economic significance.

As a matter of fact, for quite a few years the EU has unabashedly been one of the leading players – if not the leading player – in bioelectromagnetic research efforts, both at the European Commission (EC) level and by individual countries. (Support for bioelectromagnetics research from some East Asian countries was a close second in terms of funding and number of projects.) A recent report, issued by EMF-NET (http://www.jrc.ec.europa.eu/emf-net), offered a lengthy list of European projects on the biological effects of power-line and wireless-communication electromagnetic fields. The list also included projects on potential risks related to exposure in the working environment, i.e., occupational exposure.

The EMF-NET project is an initiative of the EC, and is entitled "Effects of the Exposure to Electromagnetic Fields: From Science to Public Health and Safer Workplace." This four-year project, to conclude in 2008, is one of the most ambitious and all-encompassing programs funded by the EC to date. It targets exposures from a wide range of non-ionizing electromagnetic-energy-emitting devices, sources, and systems, including power lines, cellular mobile phones, base stations, broadcasting antennas, and household electrical appliances such as mixers and induction ovens (IH hobs), as well as various electromagnetic equipment found in industrial environments and health-care facilities. The main task of EMF-NET is to review and interpret research results on the possible health impacts of exposure to electromagnetic fields. Its objective is to providing information to regulatory bodies and industry, and to support "informed decision making" by health and environmental authorities and consumer associations, as well as individuals (specifically, Europeans). Thus, it has the important role of providing the European Commission and other governing bodies appropriate information to facilitate policy development options on the safety of exposure to electromagnetic fields.

Although the recent report was a first report, when updated with analysis of the way research projects are planned, funded, and conducted in Europe, it may serve as the basis for more ambitious future reports aimed at improving bioelectromagnetic research in Europe, in view of the ever-changing new technology development, attendant scientific needs, and the necessary funding levels.

In addition to support from the EC, Table 1 lists the number of projects, funding, and average duration of ongoing research projects by country in Europe, as of May 2006, and documented in the recent report. In total, there are 240 projects distributed among 13 countries. Note that seven of the 13 countries listed have organized national research programs, namely Denmark, Finland, France, Germany, Italy, Switzerland, and the UK. The total amount of funding is 46,730 K€ ($53.74M, based on 1€ = $1.15), which computes to about 195 K€ ($242,000) per project. The average duration of each project is approximately 33 months, and the average funding is 78 K€ ($89,700) per project, per year.

Scientific research programs may be organized using two major approaches: exploratory and mission-oriented research. The strategies through which this research may be organized and supported are distinct because of their complexity. Exploratory research is generally hypotheses-driven: its objective is to gain knowledge and learn about the interaction of EMF from electric power transmission, distribution, and utilization, and under artificial environments of cellular mobile telephony, in the present subject. Mission-oriented research has as its objective a

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specific goal, for example, to discover whether brain tumors may result from use of mobile telephones, as a case in point. It appears that most research projects listed in the report fall under both the categories of mission-oriented research and exploratory research.

This is in sharp contrast to the scenario in the United States, in the recent past. The strategy had been to devote millions of dollars (mostly underwritten by industry) per project, per year, to a limited number of studies, given to a small number of research groups. However, some in the US (including the author) have recommended to no avail an alternative strategy or paradigm, paired with governmental financial commitment. The amount of research expenditure was not huge by program standards, nor was it small. If managed like the ongoing European research effort, the expenditures could have supported at least one hundred projects on the order of $250,000 each per year. Note that scientific approach and knowledge are predicated on replication and confirmation by repeated experimentation. The problem of health implications cannot be met without the presence of a critical mass of scientists working on issues that are crucial to the interaction of cell-phone RF radiation with biological systems. The uncertainties of the linkage between wireless mobile communication systems and their health effects persist today, in part, because of the limited number and scope of studies that have been conducted or completed. It is fair to say that the research efforts in the US have not helped to overcome the current situation.

The difficulties encountered by scientists and engineers in the US have impacts that extend well beyond the bioelectromagnetics research community. By forgoing the strategy to engage and support a larger number and a wider range of scientists, the US has missed out on an opportunity for research capacity building in the biological, physical, and engineering sciences.

The list of projects in the EMF-NET report included the development of some of the most innovative radio-frequency exposure systems. These projects also involve the use of cutting-edge techniques in genomics, proteomics, and transcriptomics. Clearly, colleagues in Europe are moving ahead on the frontiers of bioelectromagnetics research. As a consolation, perhaps one day in the not too distant future we may all enjoy the fruits of their research endeavor. In the meantime, let’s hope that their initiatives do not suffer from problems that have made it all but impossible for some of the past projects to meet even minimal responsibilities.

Country	**Number of Projects**	**Total Funding(K▯)**	**Average Duration (Months)**
Austria	11	1,744	30
Belgium	1	74	6
Switzerland	17	1,666	21
Germany	53	1,500	29
Denmark	9	380	36
Greece	2	140	35
Spain	8	927	46
Finland	15	1,629	24
France	22	1,670	32
Italy	42	6,557	37
Netherlands	6	680	58
Sweden	11	2,175	29
UK	43	27,588	39

Table 1. Ongoing research projects by country in Europe

Conferences

CONFERENCE REPORTS

11TH WORKSHOP ON THE PHYSICS OF DUSTY PLASMAS

Williamsburg, Virginia, USA, 28 June - 1 July 2006

The 11th Workshop on the Physics of Dusty Plasmas was held from June 28 to July 1, 2006 at the Woodlands Hotel and Suites in historic Williamsburg, Virginia, USA. The meeting was hosted by the US Naval Research Laboratory and Virginia Tech University. In addition to the International Union of Radio Science (URSI), other sponsors of the meeting included the US Department of Energy, the US Naval Research Laboratory (NRL), and the Office of Naval Research (ONR). The scope of this meeting covered the entire range of dusty plasma physics, including:

- Basic and Applied Science Topics
- Laboratory Experiments
- Space Observations
- Theory and Simulations
- Microgravity Experiments

Two and one-half days of oral and poster presentations were given at the Workshop. The Workshop itself was held at The Woodlands due to the excellent meeting facilities and their prime location near the heart of Colonial Williamsburg. In addition to the Workshop, conference attendees were also able to learn more about America's 18th century history.

The meeting opened on June 28 with welcoming remarks by conference organizers (and URSI members) Bill Amatucci of the US Naval Research Laboratory and Wayne Scales of Virginia Tech University. Immediately following those remarks, oral presentations began.

Four talks we given in the opening session. The general theme of the first session was Space/Microgravity. The opening talk of the conference was an excellent presentation by Mihaly Horanyi (U. Colorado/URSI member) on Saturn's Spokes. This was followed by presentations on the clustering of dust particles in astrophysical plasmas by Lorin Matthews (Baylor Univ.), the laser manipulation of particles under microgravity by Matthias Wolter (Univ. Greifswald), and the development of a spectrometer for the sampling of mesospheric aerosol particles by Zoltan Sternovsky (LASP/U. Colorado/URSI member).

The Space/Microgravity theme was revisited in oral presentations on the second day of the workshop. Those presentations included a discussion of the PK-4 experiment for the study of dusty plasmas aboard the International Space Station by Markus Thoma (Max Planck Inst.). Also included were discussions of dust dynamics and transport near planetary surfaces by Josh Colwell (LASP/U. Colorado), a statistical charging model for active perturbation of plasma irregularities associated with the summer polar mesosphere by Chen Chen (Virginia Tech.). Paul Bernhardt (NRL) gave a presentation on a proposed sounding rocket project called the Charged Aerosol Release Experiment (CARE).

Many other interesting areas regarding the physics of dusty plasmas were covered as well. Some Workshop presentations focused on nanoscale grains in dusty plasmas, such as Scott Roberson's presentation on "Smoky Plasma" and Steve Girshick's presentation on the spatiotemporal evolution of a nanodusty RF plasma. Other presentations focused on the dynamics of charged microparticles, such as Alexander Piel's (U. Kiel) presentation on laser-excited shear waves, Yevgen Martysh's (Taras Shevchenko National Kyiv University) presentation on dust ion-acoustic nonlinear structures, and Yuriy Ivanov's (Univ. Greifswald) discussion of the dynamics of 3D Coulomb balls to name a few.

Of course, theoretical work and computer simulations were well represented at the Workshop as well. This work included discussion of nonlinear theories of void formation in dusty plasmas by Amitava Bhattacharjee (UNH), a presentation on a Monte-Carlo particle-in-cell code to study the interaction of dust grains with UV radiation by Victor Land (Fom Institute for Plasma Physics, the Netherlands), and calculations of the potential and dynamical charge on a moving microparticle by Muhammad Shafiq (Royal Institute of Technology, KTH).

Overall, the Workshop was very successful. The organizers have arranged for a special issue of IEEE Transactions on Plasma Science to publish papers from the workshop. This issue is tentatively scheduled for April of 2007.

On behalf of the organizers and the Workshop participants, I would like to thank URSI for their support of this meeting.

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3RD IAGA/ICMA WORKSHOP ON VERTICAL COUPLING IN THE ATMOSPHERE/IONOSPHERE SYSTEM

Varna, Bulgaria, 18 - 22 September 2006

The 3rd IAGA/ICMA Workshop on "Vertical Coupling in the Atmosphere/Ionosphere System" was held at the five-star "Grand Hotel Varna" located in the famous Bulgarian seaside resort "St Konstantin and Elena" near Varna, Bulgaria, during September 18 – 22, 2006. The meeting was attended by a total of 77 senior and young scientists from 17 countries. During the 5 days of the workshop the participants presented 85 papers, from which 34 were solicited presentations.

The aim of this workshop was not only to address the physics behind the forcing mechanisms that originate in the lower atmosphere and play an important role on the upper atmosphere and ionosphere, but also to show the solutions of some of the problems which were only formulated during the 2nd IAGA/ICMA Workshop held two years ago in Bath, UK. The meeting was designed so that research experts form both the middle and upper neutral atmosphere and ionosphere communities come together in order to present their work and assess/debate ongoing issues relating to the theoretical, modelling and observational aspects of all kind of processes which transfer energy and momentum from the lower atmosphere to the upper atmosphere and ionosphere and vice versa.

The programme focussed on various aspects and topics of neutral dynamics as well as ionospheric electrodynamics and plasma physics. These included:

1) Coupling processes in the middle atmosphere

- Coupling through planetary waves, mean flows and temperature variability
- Gravity wave and tidal forcing of the middle atmosphere
- The role of dynamics, solar variability and greenhouse gasses on the chemical structure and feedback processes

2) Coupling processes in the atmosphere/ionosphere system

- Dynamical forcing of the ionosphere from below
- Electrodynamic coupling and plasma instabilities; the role of electrical processes in the coupling

This workshop brought together a mix of scientists doing mostly independent research on the fields of the MLT neutral atmosphere and the ionosphere, that is, on two collocated "spheres" of the near earth environment which remain closely coupled and on a continuous interaction. The meeting provided an excellent opportunity for these research communities to interact in a supplementary manner in reviewing and debating the progress done to date in the field of the upper atmosphere-ionosphere and come up with suggestions and ideas for further research on the vertical coupling of the atmosphere-ionosphere system.

Financial contributions to the workshop were made by the following organisations: the International Union of Radio Science (URSI), International Association of Geomagnetism and Aeronomy (IAGA), International Commission on the Middle Atmosphere (ICMA), International Union of Geodesy and Geophysics (IUGG) and US Airforce European Office for Aerospace and Development (EOARD). In particular, the URSI contributed with a grant of 500 EUR. This grant was used for supporting part of the travel and living expenses of one solicited speaker: Prof. Giorgi Aburjania from Tbilisi State University, Tbilisi, Georgia.

The presentations at this Workshop will be published in a special issue of JASTP. The team of Guest Editors includes: Daniel Marsh (NCAR, Boulder, USA), Mike Taylor (Utah State University, Logan, USA), Christos Haldoupis (University of Crete, Iraklion, Greece) and Dora Pancheva (University of Bath, Bath, UK).

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2ND VERSIM WORKSHOP
ELF/VLF RADIO PHENOMENA: GENERATION, PROPAGATION AND CONSEQUENCES IN OBSERVATIONS, THEORY AND MODELING

Sodankylä, Finland, 26 - 30 September 2006

Overview

The 2nd VERSIM Workshop took place last month at the Sodankylä Geophysical Observatory, sponsored by the Observatory and supported by IAGA and URSI Commission H. This was a chance for the VERSIM IAGA/URSI joint working group to meet and discuss current issues, developments, and techniques. The workshop attracted about 46 participants from 16 countries, ranging from Fiji and Slovenia all the way to Brazil and the USA, and included 52 presentations. The participants spanned from 9 young researchers all the way to real pioneers in our field. We were proud to welcome Don Carpenter, who using VLF whistlers was crucial to discovery of the plasmasphere, and

Don Carpenter (Stanford, USA), framed by a SGO VLF antenna.

is in a real sense the "father of VERSIM". The 2nd VERSIM Workshop included four of the previous six VERSIM co-chairs, and both the current co-chairs (Rodger (New Zealand) and Lichtenberger (Hungary)). There were a particularly strong series of presentations on remote sensing of the upper atmosphere through subionospheric VLF propagation and on the properties and effects whistler mode waves observed on the ground and in space, particularly focused on VLF chorus emissions. A full listing of abstracts can be found at: *http://www.sgo.fi/Events/versim-2006/abstracts.php*

This workshop follows on from the 1st VERSIM Workshop, which also took place at the Sodankylä Geophysical Observatory, at almost the same time in 2004. The success of the first meeting attracted 50% more participants and 40% more presentations. Even with the additional presentations the workshop timetable was fairly relaxed, allowing oral presentations to of a sensible length (~20-30 min). In addition, there were also good-length coffee and lunch breaks in which participants could follow up with more detailed discussions, or plan future scientific collaborations. Once again, the facilities and organisation was of a very high standard, and at the end of the 2nd VERSIM Workshop the participants gave a vote of thanks to the Local Organising Committee for running the workshop so smoothly. A vast number of the Observatory staff were involved in supporting the Workshop, from transporting participants to and from the airport, to setting up a display of VLF antenna.

As part of the IAGA support for the 2nd VERSIM Workshop, an award was offered for the best paper presented by a young researcher. The award consists of support to participate in the next IAGA General Assembly: a low-cost air ticket, waiving of the registration fee, plus one days costs. The Programme Committee of the 2nd VERSIM Workshop unanimously proposed Ms. Annika Seppälä for the IAGA Young Scientist Presentation Award. Ms. Seppälä is a Research Scientist at the Finnish Meteorological Institute, and is undertaking research towards a PhD. Her presentation focused on the significance of the January 2005 solar proton events upon the ozone levels in the polar atmosphere. A combination of experimental data, both space and ground based, were combined with chemical modelling. Ms. Seppälä demonstrated the production of ozone-destroying chemicals

The 2nd VERSIM Workshop, group photo at Mattila's Reindeer Farm.

Annika Seppälä, winner of the IAGA Young Scientist Presentation Award, at the Ice Breaker function, Sodankylä Municipality Hall

due to the impact of the solar proton event upon the polar atmosphere at altitudes from 30-80 km. Her paper also points to the power of combined observations, taking the experimental techniques employed by the VERSIM community into a new and highly important scientific area. Ms. Seppälä nomination by the Workshop Programme Committee has been confirmed by the IAGA Executive Committee. Well done Annika!

Social Events and Excursions

As with all successful scientific meetings, there were a number of excellent social events and excursions to broaden the experience of the Workshop participants. Our excursions included a display of VLF antenna inside the Sodankylä Geophysical Observatory ground, prompting some theorists to comment it was the first time they had seen an operational antenna system "in the flesh". We also visited the nearby Finnish Geological Survey laboratory, SGO's nearest measurement station Pittovaara, and a local jewellery manufacturer.

The 2nd VERSIM Workshop social programme opened with an "Ice Breaker" function supported by the Sodankylä regional Government at the Sodankylä Municipality Hall. For many of the participants this was the first opportunity to sample a range of food and drinks from Lapland. The conference dinner took place at an operational reindeer farm, which also hosts tourists so as to keep this traditional Lappish activity economic. After viewing some of the reindeer herd, including a magnificent and aggressive white stag, we retired into the warmth of the banqueting hall for generous helpings of delicious smoked reindeer. Our Hungarian colleges provided small samples of Hungarian "Palinka", perhaps as an indication of the pleasures to come at the 3rd VERSIM Workshop, and the 2009 IAGA meeting in Sopron.

Some idea of the success of this session can be found on the Photos page of the 2nd VERSIM Workshop 2006: *http://sgodata.sgo.fi/pub/VERSIM_photos/VERSIM_photos.html*

Future

At the end of the 2006 Workshop it was felt that the meeting had been a large success, and that the community had gained a new momentum on the basis of the 1st and 2nd VERSIM Workshops. A unanimous vote of thanks to our Finnish collaborators was agreed, as the two Workshops they have hosted have brought a new vibrancy to the VERSIM working group. To maintain the momentum, the community accepted the invitation of Dr. János Lichtenberger, the URSI co-chair of the working group to host the 3rd VERSIM Workshop in Tihany, Hungary. This is now planned for the week starting 15 September 2008, on the shores of Lake Balaton.

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INTERNATIONAL REFERENCE IONOSPHERE WORKSHOP 2006: NEW MEASUREMENTS FOR IMPROVED IRI TEC REPRESENTATION

Buenos Aires, Argentina, 16 - 20 October 2006

The 2006 IRI Workshop was held at the hotel "El Conquistador" in the heart of Buenos Aires exceptionally well organized by Dr. M. Mosert with her team from CASLEO, San Juan and with help from the ionospheric groups from the Universidads Nacional of Tucuman and La Plata. The close to 60 participants represented many countries (Argentina, Czech Republic, Italy, USA, Spain, Russia, Austria, Peru, Cuba, South Africa, Brazil, Nigeria, and Mexico) and many different data sources (ionosondes, GPS, incoherent scatter radars, TIMED, DMSP, Hinotori, Akebono and a few other satellites).

The week long meeting was divided in sessions entitled "TEC Data and Modeling", "Topside", "Lower Ionosphere", "Disturbed Ionosphere", "Data Sources for IRI", "F Peak and Bottomside", "Temperatures", and "Posters".

The meeting was financially supported by the Committee on Space Research (COSPAR), the International Union of radio Science (URSI), the US National Science Foundation (NSF), the US Air Force Office of Scientific Research (AFOSR), the Abdus Salam International Center for Theoretical Physics (ICTP), the Italian Instituto Nazionali di Geofisica e Vulcanologia (INGV), the Italian Embassy in Argentina, and several Argentine institutions including Consejo Nacional de Investigaciones Cientificas y Tecnicas (CONICET), Secretaria de Ciencia Tecnologia e Innovacion Productiva – Agencia Nacional de Promocion Cientifica y Technologica (SECYT-ANPCT), Complejo Astronomica "El Leoncito" (CASLEO), Universidad Nacional de San Juan (UNSJ), Facultad Regional Tucuman, Universitad Tecnologica Nacional (FRT-UNT), Universidad Nacional de Tucuman (UNT), Facultad de Cienccias Astronomicas y Geofisicicas de la Plata - Universidad Nacional La Plata (FCAGLP-UNLP), Fundacion Para el Avance de la Ciencia Astronomica (FUPACA), Congreso de la Nacion Argentina, Gobierno de la Provincia de San Juan - Ministero de Infrastructura y Tecnologia, and Ana Allende Trust. The workshop was also the backdrop for the signing of an Italian-Argentine technology transfer agreement, which will provide the ionospheric group in Tucuman with an Italian-build ionosonde. This complements a US Air Force Digisonde that is being installed in San Juan. Memorable highlights were a tour of the city of Buenos Aires, the Workshop Banquet in one of Buenos Aires oldest Tango Dinner Theaters, and a visit to the Argentine Congress. More details are available on the workshop home page http://www.casleo.gov.ar/IRI2006/

Lower Ionosphere

McKinnell (South Africa) presented a new version of her NeuralNet IMAZ model for the auroral lower ionosphere. It now uses solar zenith angle and Ap index as input parameters and includes a special version that runs without the absorption value input that is required for the standard model. This version is now scheduled to be included in IRI-2006. Friedrich (Austria) introduced his first attempt at representing the electron density in the polar cap using the NN technique. The model reaches up to the F-region and describes variations with day-of-year, altitude, Kp, F10.7, and solar zenith angle based on 6 years of EISCAT Svalbard incoherent scatter measurements and on 371 profiles from Heiss Island rocket measurements. Comparisons with IRI indicate that the extrapolation of IRI into the polar cap produces values that correspond to fairly disturbed conditions.

Bottomside

A number of papers dealt with the three parameters (B0, B1, D1) that define the shape of the bottomside electron density profile using ionosonde data from several European and South African stations (Buresova, Czech Republic) and from Ilorin, Nigeria (Adeniyi, Nigeria). The long-term goal is to replace the current tabular form of the IRI model with appropriate mathematical functions similar to what had been proposed at the Beijing IRI session by Altadill (Spain) for the seasonal and diurnal variations of these parameters. Reinisch and Huang (UML, USA) noted abrupt changes in the F1 region electron density due to discontinuities in the model for the F1 layer thickness parameter D1 and suggested improvements. Coisson, Radicella, Nava (Italy), Adeniyi (Nigeria), and Savio (Cuba) note that in some cases the large bottomside profiles observed at low latitudes (Ascension Islands, Jicamarca, Ilorin) are severely underestimated by IRI even to the point of affecting the TEC. Correction of this problem will be an important element of the new B0 modeling initiative.

F peak

IRI currently includes two options for the F2 peak frequency (foF2), CCIR-67 is recommended for the continents and URSI-88 for the ocean areas. A large volume of ionosonde data has accumulated since these models were build and the IRI team has encouraged efforts to establish an improved model for the whole globe. Oyeyemi and McKinnell (South Africa and Nigeria) presented first results of such a new modeling attempt. They trained a Neural Net (NN) with foF2 from 85 global stations covering the years 1976 to 1986 and 1995 to 2005. Data were obtained through NGDC-SPIDR, UML-DIDBase, and IPS-services. Input parameters are day-of-year, UT, solar zenith angle, geographic latitude, magnetic inclination and declination, and magnetic and solar index. First result are very promising and indicate better performance than the CCIR and URSI NmF2 models currently used in IRI. The authors asked for more data to further improve their model and were promised new inputs from the Brazilian ionosondes and from topside sounder satellites. One hindrance in earlier modeling efforts were data quality problems with the long-term ionosonde data record. The IRI team had contacted the NGDC to point out specific problems with ionosonde data from their SPIDR system. Denig and Redmon (USA) representing NGDC at the meeting reported that many of these problems have now been resolved or are being worked on actively. Ezquer (UNT, Argentina) studied data from 14 South and Middle American ionosonde stations and found that the sunrise minimum in foF2 is often shifted by 1 or even 2 hours compared to the CCIR and URSI foF2 model; fewer such cases are seen with the CCIR model. A likely cause could be the use of a sector Local Times instead of Solar Local Times for the ionosonde data that were used in developing the CCIR and URSI maps.

Souza, Abdu and Batista (Brazil) presented a new version of their spread F occurrence probability model for Brazilian longitudes. The new model uses Bernstein polynomials as base functions, a higher resolution with solar activity, and assumes latitudinal symmetry with respect to the magnetic equator. Comparisons with measurements during the Conjugate Point Equatorial Observational Campaign (COPEX) show good agreement. This latest version of the model will become part of IRI-2006. The group plans to extend their model to other longitudes using topside sounder data and other ionosonde data specifically from the Indian subcontinent.

Efforts continue to include a description of ionospheric variability (quartiles, deciles) in IRI. Ezquer (UNT, Argentina) extended these studies to Antarctic latitudes with data from the Argentine Ellsworth station finding largest relative variability in winter (dark ionosphere) and data distributions that are skewed towards lower values. The ionospheric group of the Instituto de Gefisica y Astronomia in Havanna, Cuba has been very active in this area using a global set of ionosonde data. Lazo (Cuba) presented an overview of the activities of this group and a good summary of their variability work. Here the improved data quality of the SPIDR data will be also of great benefit.

Topside

With the availability of real-time TEC from many GPS receivers on the ground and aboard satellites, e.g., the recently launched COSMIC constellation, updating of IRI with TEC measurements is a topic of great interest. The ingest procedure of Nava, Radicella and Coisson (Italy) adjusts the IRI slant TEC to measured values with the help of an effective solar index. Meza, Gularte, Brunini (UNLP, Argentina) and Mosert (CASLEO, Argentina) presented a scheme for deducing Vary-Chap parameters for the topside profile from combining GPS and ionosonde data. The Vary-Chap approach as introduced by Reinisch, Nsumei, and Huang (UML, USA) represents the topside profile with a modified Chapman-function assuming a variable scale-height. Reinisch (UML,USA) presented the most recent results of the UML group including seasonal and latitudinal variation of Vary-Chap parameters deduced from ISIS topside sounder data. One of the Vary-Chap parameters is the scale height at the F-peak. Altadill (Spain) presented an empirical model for this parameter based on one solar cycle worth of data from the Ebro Digisonde. Scale heights obtained with the Grahamstown ionosonde were studied by Nambala, McKinnel, and Oyeyemi (South Africa). The scale height is largest in summer and lowest in winter and reaches its diurnal maximum during mid-day and exhibits a close correlation with the bottomside thickness parameter B0 and with the slab thickness. A 4-D modeling of the ionospheric electron density based on IRI and GPS measurements was described by Schmidt (Germany), Bilitza (GSFC, USA), and Shum (OSU, USA). Garner (UTD, USA) is undertaking a very comprehensive analysis of the large DMSP data set of electron density measurements at 850 km altitude. Of the 3 DMSP instruments measuring electron density (Retarding Potential Analyzer, Scintillation Cup, Ion Drift Meter), the RPA seems to give the most reliable results. Depuev (Russia) and Pulinets (Mexico) described a data base of more than 8,000 manually scaled topside ionograms from the Intercosmos-19 satellite covering the high solar activity years 1979 to 1981 and of about 2000 ionograms from Cosmos 1809 for the low solar activity year 1989. This will be an excellent data source for the foF2 modeling effort of the South African group (see previous section)

TEC and GPS

Hernandez-Pajares, Juan, and Sanz (Spain) described their technique for estimating medium-scale (period<20 min) traveling ionospheric disturbances (MSTIDs) from GPS measurements and a first assessment of the occurrence probability of MSTIDs. Maps of VTEC for South America are produced hourly by the GESA laboratory of La Plata University (Brunini, Meza, Gends, Azpilicueta, UNLP, Argentina) using data from all available GNSS receivers and applying a special de-biasing procedure. Ionosonde and GPS data from Brazil show that IRI underestimates the EA intensity and the TEC during nighttime in the Brazilian sector (Abdu et al., Brazil) for all levels of solar activity. Fuller-Rowell, Araujo-Pradere, and Codrescu (SEC, USA) estimate that even with a dense network of GPS dual-frequency ground receivers (like the more than 600 receivers in the US) an uncertainty of 2-4 TECU remains in the determination of real-time TEC. Garner (UTD, USA) presented the ARL:UT GPS toolkit (GPSTk) and described ARL's Ionospheric Data Assimilation Three Dimensional (IDA3D) model that accepts data from ground and satellite GPS receivers, from satellite beacons, from TOPEX, from insitu measurements, and from ionosondes. He also presented first results from the recently launched COSMIC beacons (CERTO) and cautioned that all TEC measurements contain an unknown bias and are best used for studying changes in TEC. Pulinets (Mexico) studied the response of GPS-TEC to positive D_{st} pulses (solar flares, magnetopause currents) noting strong positive deviations up to 50%.

TOPEX ionospheric data are a valuable data source for studying VTEC (Azpilicueta, Meza, and Brunini, UNLP, Argentina), however, it is important to agree on a common method for averaging and grouping the TOPEX (and other satellite altimeters, like Jason and Envisat) data before applying this analysis to IRI (Radicella, Italy). Migoya, Ezquer (UNT, Argentina), and Radicella, Coisson (Italy) used TOPEX data to evaluate the new IRI-NeQuick option against the older IRI-2001 topside model. Both models show good agreement with the data with IRI-2001 producing slightly better results.

ITEC measurements by Digisondes based on the assumption of a Chapman topside layer were compared with GPS TEC measurements for stations in Spain (Mosert, CASLEO, Argentina) and South Africa (Paradza, McKinnell, Opperman). The difference between the two is the plasmaspheric electron content which is about 2 -3 TECU and can reach up to 20-30% of the TEC at nighttime during low solar activity.

Temperatures

Bilitza (GSFC/Raytheon, USA), Richards (NASA, USA), Truhlik and Triskova (Czech Republic) studied the solar activity variation of the topside electron temperature and found discrepancies between DMSP measurement, the Millstone Hill ISR model, and the FLIP model, most importantly unrealistically high temperatures at low solar activities and ISR data that are consistently lower than DMSP and FLIP values. In a follow on talk by the same authors, Truhlik described a method for including solar activity variations in a new IRI electron temperature model. Rocket measurements of abnormally large electron temperatures in the equatorial ionosphere over Brazil were reported by Muralikrishna (Brazil).

Data Sources for IRI

Representatives from the Jicamarca and Arecibo Incoherent Scatter Radar (ISR) facilities reviewed the capabilities of their ISR systems and the potential use of their data for IRI improvements. Ilma and Chau (Peru) find that IRI underestimates Jicamarca ISR topside electron densities during daytime and overestimates the ISR densities during nighttime. Aponte (NAIC, USA) described recent developments at the Arecibo ISR and presented examples of comparisons with IRI. IRI reproduces qualitatively the general features of the topside ionosphere over Arecibo with best results for the ion composition and ion temperature. A comprehensive evaluation of the IRI-2006 model with the many years of Jicamarca and Arecibo data is highly encouraged and would surely result in major improvements of the IRI model. Rich (AFGL, USA) announced the availability of a number of data sets from his website https://swx.plh.af.mil (password required) including DMSP ionospheric data from 1987 to present, CHAMP Ni, Te at 400 km, Apex Ni, Te from 1994 to 1997.

Denig and Redmon (NGDC, USA) reported on the restructuring of the ionosonde program within NGDC and on efforts to restore the confidence in the quality of the SPIDR ionospheric data. They will work closely with the IRI team, who had brought up these data quality problems at its 2003 Workshop. Several of these issues are now corrected.

Krause (USAFA, USA) described a project that the US Air Force Academy (USAFA) is in the process of developing to investigate the southern crest of the Equatorial Anomaly in the region near San Juan, Argentina. It consists of a series of ground based (Digisonde, GPS receivers) and space based (FalconSAT-3, FalconSAT-4) experiments. The use of TIMED/GUVI and DMSP/SSUSI electron density measurements for improvements of the IRI model was discussed by DeMajistre, Paxton, and Kil (JHU/APL, USA), with special emphasis on the F peak height and the O^+ topside content.

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CONFERENCE ANNOUNCEMENTS

10^{ÈME} ANNIVERSAIRE: COLLOQUE INTERNATIONAL TELECOM '2007 & 5^{ÈMES} JFMMA

Fes, Maroc, 14 - 16 Mars 2007

Ce colloque est organisé par l'ESTF de l'USMBA en collaboration étroite avec les institutions scientifiques françaises, en particulier l'Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN), Lille, France. Cette manifestation scientifique est un des aspects d'accords de coopération inter-universitaires. Le Colloque est parrainé par : l'URSI , IEEE section Maroc et le ClubEEA.

Objectifs

Télécom'2007 & 5^{èmes} JFMMA sera la 6^{ème} manifestation scientifique d'une série de conférences internationales traitant des radiofréquences, des micro-ondes, de l'optoélectronique, des microsystèmes, des nanotechnologies, , des télécommunications, de la CEM, du traitement du signal et des images etc….

Depuis leur création en 1996, ces conférences ont connu une grande réussite, en permettant aux scientifiques travaillant dans ces thématiques non seulement d'échanger leurs résultats de recherche mais aussi de nouer de nouvelles collaborations internationales.

Thèmes de la Conférence

A) Micro-Ondes & Optoélectronique

- Instrumentation et mesures
- Capteurs micro-ondes et Microsystèmes
- Radars
- Composants micro-ondes et optoélectroniques
- CAO des circuits micro-ondes
- Caractérisation en micro-ondes et optoélectronique
- Applications médicales et industrielles des micro-ondes

B) Télécommunications & TIC

- Systèmes de télécommunications (RF, Mobiles, Satellites…)
- Antennes
- Communications optiques
- Réseaux de télécommunications
- Protocoles de communication
- Internet, Multimédia

C) Comptabilité Electromagnétique

- Couplage avec les structures et les systèmes
- Techniques et systèmes de mesures
- Modélisation numérique en CEM
- Vulnérabilité des systèmes et des circuits
- Normes, recommandations, spécifications etc…

D) Transmission et Traitement d'Images

- Transmission et compression d'images
- Restauration d'images
- Télédétection etc …

E) Nanoélectronique– Nanotechnologie

- Matériaux , caractérisation
- Nano-tubes et nano-fils de carbone, transistors de carbone….

Comité Scientifique

Président : A. Mamouni, IEMN, USTL
Vice-Président : B. Demoulin, IEMN, USTL

Dates Importantes

- Mai 2006: Appel à communications
- 15 octobre 2006: Date limite de soumission des textes complets
- 15 décembre 2006: Notification d'acceptation des communications
- 31 janvier 2007: date limite d'inscription au tarif normal

Informations & Contacts

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Fax. : 33 (0) 3 20 19 78 80
GSM : 33 (0) 6 88 88 89 19

Au Maroc
Prof. M. El Bekkali et Prof. A. Benbassou
Ecole Supérieure de Technologie de FES/ESTF.
Route D'Immouzer - BP: 2427 – 30000 Fès - MAROC
Tél.: 00 212 (0) 35 60 05 85/86
Fax: 00 212 (0) 35 60 05 88
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E mail:
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moulhime_el_bekkali@hotmail.com
Site Web: http//www.est-usmba.ac.ma/telecom2007/

ASTROPHYSICS IN THE LOFAR ERA

Emmen, the Netherlands, 23 - 27 April 2007

General

The LOw Frequency ARray is a new generation radio telescope which will observe the low frequency sky with unprecedented resolution and sensitivity. The first core station of LOFAR (CS-1) is currently being assembled near Exloo and has begun producing data. Soon LOFAR will grow rapidly after the critical design review in early 2007.

The purpose of the workshop is to bring together prospective users of LOFAR to explore current and future science perspectives of low-frequency radio observations and is sponsored by LOFAR, ASTRON, RadioNet and URSI.

Participants are invited to discuss their current science results and propose future projects with LOFAR. We hope to establish an excellent basis for collaborations within the user community. Furthermore, this workshop will provide an introduction to the LOFAR system and its initial scientific drivers. Results from prototype facilities such as ITS (Initial Test Station), Westerbork High-band Antenna Tile and CS-1 (Core Station 1) and potentially from other existing low-frequency facilities will be presented. A visit to the LOFAR core site in Exloo is included.

The workshop will be held at a lake-side holiday resort near Emmen 20 km South of the LOFAR core. The programme will include a number of recreational and social activities, such as football and bowling. The conference fee includes all meals and accommodation. Participants will be housed in modern vacation bungalows with individual bedrooms, and three people sharing a lounge, kitchen and two bathrooms.

U.R.S.I.

Commission B-EMTS

EMTS 2007

CALL FOR PAPERS

General Information

In a long tradition, Commission B, "Fields and Waves", of the International Union of Radio Science (URSI) organizes a triennial series of International Symposia on Electromagnetic Theory. The 2007 International Symposium on Electromagnetic Theory will be held in Ottawa, ON, Canada, July 26 – 28th, 2007. The scope of the Symposium covers all areas of electromagnetic theory and its applications. The working language of the Symposium is English. There will be a limited number of Young Scientist Awards (YSA) available for application.

Paper Submission

Authors addressing advancement and describing innovation in all areas of electromagnetic theory and its applications and other topics of interest to URSI are invited to submit their contribution for review and presentation in the symposium. Suggested topics are listed here. Submissions must be 3-pages, and submitted electronically in pdf format through the conference website. Submissions and applications for the Young Scientist Award must be received by February 1st, 2007, and all other submissions by February 15th, 2007. Further instructions for paper preparation, electronic submission, and the YSA application, will be available on the website. Registration and other information on the Symposium will also be posted to the website upon availability.

http://emts2007.ee.umanitoba.ca

Symposium Location

The Symposium will be held at the Fairmont Château Laurier, located in the heart of Canada's capital city, Ottawa. This landmark hotel is a magnificent limestone edifice with turrets and masonry reminiscent of a French château and is situated next door to Canada's Parliament Buildings.

Symposium Schedule

1st Feb. 2007
Deadline for receipt of YSA papers and YSA applications.
(only electronically submitted papers via the website will be accepted)

15th Feb. 2007
Deadline for receipt of all papers.
(electronic submission via the website only)

15th Apr. 2007
Notification sent to authors for acceptance of papers and Young Student Award papers

15th May 2007
Deadline for pre-registration
(Presenting authors must pre-register)

26th- 28th July 2007
Symposium

JULY 26-28, 2007

http://emts2007.ee.umanitoba.ca

Fairmont Château Laurier,
Ottawa, ON, Canada

Topics

Contributions concerning all aspects of electromagnetic theory and its applications are welcome. Other organized sessions will be indicated on the paper submission page of the website. Novel and innovative contributions are particularly appreciated.

Basic Electromagnetic Theory
R1 Electromagnetic theory
R2 Mathematical modelling of EM problems
R3 Solutions to canonical problems
R4 Non-linear phenomena

Scattering and Diffraction
R5 Scattering and diffraction
R6 High-frequency methods
R7 Inverse scattering and imaging

Random, Inhomogeneous, Nonlinear and Complex Media
R8 Propagation and scattering in layered structures
R9 Random media and rough surfaces
R10 Complex media
R11 Beam and pulse propagation and scattering in lossy and/or dispersive media

Computational Techniques
R12 Numerical methods: general aspects
R13 Numerical methods for integral and differential equations
R14 Hybrid methods

Transient Fields
R15 Time domain methods
R16 Radiation, scattering and reception of transient fields and/or wideband signals

Guided Waves
R17 Guided waves

EMC/EMI
R18 Interaction of EM waves with biological tissues
R19 Modelling Techniques for EMC/EMI

Antennas
R20 Antennas: general aspects
R21 Antenna arrays, planar and conformal
R22 Smart antennas
R23 UWB antennas Systems
R24 EM theory and applications for radio systems
R25 Antennas and propagation for communication systems: Mobile, LAN etc.

Others
R26 Others (*please indicate your specific field*)

Special Topics *(to be decided)*
Important and original papers will be selected and reviewed by the editorial board for inclusion in Radio Science. Details will be posted to the conference website.

Conference Contacts
General questions and technical program
Prof. Lot Shafai, Chair, Commission B of URSI
Department of Electrical and Computer Engineering
University of Manitoba, 75 Chancellors Circle,Winnipeg, MB, Canada R3T 5V6
E-mail: shafai@ee.umanitoba.ca
Phone: 204-474-9616 Fax: 204-269-0381

Conference Secretariat
Ms. Shelly Girardin
E-mail: emts2007@ee.umanitoba.ca
Phone: 204-474-6469 Fax: 204-269-0381

There will be invited talks featuring the LOFAR system, results from the first prototype stations and the initial science drivers for the development of LOFAR. Discussion sessions will be held and additional workgroup discussion will be encouraged.

Contributed talks and posters focusing on future LOFAR science in the context of past and current work are welcome. Abstracts for oral presentations and posters should be submitted through the conference web site before March 1st, 2007.

The Scientific Organising Committee is chaired by Dr. Heino Falcke and the Local Organising Committee is chaired by Dr. Corina Vogt.

We do not plan to publish the proceedings, but we will make the presentations available on the conference website.

If you wish to participate, please register at the workshop website: www.lofar.org/workshop/ before March 1, 2007.

Topics

- The high-redshift universe
- Stars and planets
- Astroparticle physics and astrophysical transients
- Galactic and extragalactic surveys
- Long baseline science

Contact

Dr. Corina Vogt
LOFAR Workshop
ASTRON
P.O. Box 2
7990 AA Dwingeloo
The Netherlands
Tel: +31(0)521 595100, Fax: +31(0)521 595101
E-mail conference: workshop@lofar.org
Conference Website: www.lofar.org/workshop

INTERNATIONAL SYMPOSIUM ON SIGNALS, SYSTEMS, AND ELECTRONICS (ISSSE 2007)

Montreal, Canada, 30 July - 2 August 2007

The 2007 International Symposium on Signals, Systems, and Electronics (ISSSE2007) will be held in the beautiful city of Montreal, Canada, July 30 - August 2, 2007, immediately after the 2007 URSI North American Radio Science Meeting and the URSI Commission B Electromagnetic Theory Symposium in Ottawa. The ISSSE is held every three years, and is organized under the guidance and with sponsorship of the international steering committee of URSI Commissions C and D. It has a long tradition of moving around the world: the last two previous conferences were held in Tokyo (Japan, 2001) and Linz (Austria, 2004). This event is cosponsored by the IEEE MTT-S, IEEE Montreal Section, the IEEE Montreal Joint Chapter MTTS/APS/LEOS, the École Polytechnique (Université de Montréal), and the Poly-Grames Research Center.

Topics

Technical papers in any area of interest to URSI Commissions C and D will be considered. These papers must present original contributions in the following (but not limited to) broadly-defined topics:

- Electronics for Communications, Sensing and Control, Circuits & Systems
- DSP and SDR
- Wireless, Optical and Cable-based Systems
- Devices and Techniques for RF, Microwaves and Millimeter Waves, Baseband Circuits and Photonics
- Radar Techniques and Applications
- Circuit and System Simulation
- Coding, Channel, Modulation, Detection Strategies
- Smart Antennas/MIMO Techniques, Electronic System Partitioning & Interface
- Networks & Signals
- Numerical and CAD Techniques

The language of the symposium is English. For latest news, detailed contact information, and paper submission guidelines, please visit the ISSSE2007 Web site at **www.issse2007.polymtl.ca**.

The papers will be selected through a rigorous review process. Both oral and poster sessions with invited and contributed papers will be organized. The conference will begin with keynote speaker talks. Proposals for workshops and tutorials are highly welcome, and they should be submitted by May 27, 2007, to the workshop and tutorial organizers. An industrial exhibition is also being planned. Authors are invited to submit an extended abstract of two pages prepared according to the online instructions and template by **March 25, 2007**. Only e-mail submission with a less-than-one-megabyte PDF file is allowed. The ISSSE2007 awards will be given during the symposium to the authors of the best papers, which stand for outstanding contributions to the research fields of URSI Commissions C and D. In addition, Young Scientist support will be available for selected candidates of age 35 or younger on July 30, 2007, and who have a PhD or equivalent degree.

Contact

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Ecole Polytechnique, C. P. 6079, Succ. Centre-Ville
Montreal, Quebec, Canada H3C 3A7
Tel: +1 (514) 340-4711 ext. 5991
Fax: +1 (514) 340-5892
E-mail: ke.wu@polymtl.ca or ke.wu@ieee.org

INTERNATIONAL SYMPOSIUM OF RADIO SYSTEMS AND SPACE PLASMA

Borovets, Bulgaria, 2 - 5 September 2007

We are pleased to invite you to the International Symposium on Radio Systems and Space Plasma. This meeting is sponsored by URSI, Bulgarian Academy of Science, Technical University of Sofia etc.

The symposium provides a scientific forum covering the topics of traditionally established URSI Commissions C and H (toward space plasma) and Solar Power Satellites (SPS). We plan this symposium to be concerned beginning from the intelligent methods of radio-communication systems and signal processing, through the updated methods for analyzing non-linear interactions of space plasma, up to radio science aspects of SPS systems. In addition to the general scientific sessions (Invited and Contributed talks and Posters) three plenary talks (lectures) will be prepared.

Bulgaria has a history that goes back thousands of years. Through the centuries, many peoples have inhabited it and added to its rich and diverse history. The capital Sofia is the second oldest city in Europe

Topics

- Radio-Communication and Telecommunication systems
- Spectrum and Medium Utilisation
- Information Theory, Coding, Modulation and Detection
- Signal and Image Processing in the area of radio science
- The generation (i.e. plasma instabilities) and propagation of waves in plasmas
- The interaction between these , and wave particle interactions
- Plasma turbulence and chaos
- Spscecraft-plasma interaction
- SPS Radio Technologies
- Influence and Effects of SPS-Radio Science Aspects
- Radio Science Issues for Further Study
- URSI White Paper

Website: http://www.math.bas.bg/isrssp
Email: isrssp@math.bas.bg

INTERNATIONAL CONFERENCE ON ELECTROMAGNETICS IN ADVANCED APPLICATIONS (ICEAA 07)

Torino, Italy, 17 - 21 September 2007

The tenth edition of the biennial International Conference on Electromagnetics in Advanced Applications (ICEAA 07) will be held September 17-21, 2007, in Torino, Italy. It will consist of invited and contributed papers, as well as workshops and short courses. The conference is supported by the Politecnico di Torino and by the Istituto Superiore Mario Boella, with the principal technical cosponsorship of the IEEE Antennas and Propagation Society. Other technical cosponsors include the IEEE Electromagnetic Compatibility, Electron Devices, and Microwave Theory and Techniques Societies, the International Union of Radio Science (URSI), and the IEIIT–CNR.

Topics

1. Active and smart antennas
2. Electromagnetic applications to biomedicine
3. Electromagnetic applications to nanotechnology
4. Electromagnetic measurements
5. Electromagnetic modeling of devices and circuits
6. Electromagnetic packaging
7. Electromagnetic properties of materials
8. EMC/EMI/EMP
9. Finite methods
10. Frequency-selective surfaces
11. Integral-equation methods
12. Intentional EMI

13. Inverse scattering and remote sensing
14. Microwave antennas
15. MIMO antenna systems
16. Optoelectronics and photonics
17. Phased and adaptive arrays
18. Plasma and plasma-wave interaction
19. Printed and conformal antennas
20. Radar cross section and asymptotic techniques
21. Radar imaging
22. Radomes
23. Random and nonlinear electromagnetics
24. Statistics in electromagnetics
25. Technologies for mm and sub-mm waves
26. Wireless communications

Authors of invited and contributed papers must submit a full-page abstract by **February 23, 2007**, containing sufficient information to allow the Scientific Committee to evaluate their contribution. Each submitted abstract must be accompanied by mailing address, telephone and fax numbers, and e-mail address of the corresponding author, as well as the topic number(s). Authors will be notified of acceptance by April 6, 2007, and will be given instructions for submission of the full paper to be published in the conference proceedings. ICEAA 07 requires one full registration for every paper, i.e., every paper must be accompanied by a registration fee. The full paper and non-refundable registration fee of the presenting author are due by June 1, 2007. A final program will be published and mailed in June 2007. The official language of the Conference is English.

Contact

Prof. Roberto D. Graglia
Chair of ICEAA Organizing Committee
Dipartimento di Elettronica, Politecnico di Torino
Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
E-mail: roberto.graglia@polito.it

or

Prof. Piergiorgio L. E. Uslenghi
Chair of ICEAA Scientific Committee
Department of ECE (MC 154)
University of Illinois at Chicago
851 South Morgan Street, Chicago, IL 60607, USA
E-mail: uslenghi@uic.edu.

Conference Web site: **http://www.iceaa.polito.it**

FROM PLANETS TO DARK ENERGY: THE MODERN RADIO UNIVERSE

Manchester, UK, 1 - 5 October 2007

The conference “From Planets to Dark Energy: the Modern Radio Universe” will be held from 1-5 October 2007 and is organised by the University of Manchester and to be held October 1st-5th 2007 in Manchester, UK.

Topics

This meeting will focus on the current status of future prospects for the key science themes to be addressed by the Square Kilometre Array (SKA). The SKA will have of the order of a million square metres of collecting area and will achieve a spatial resolution better than 0.1 arcsecond at 1.4 GHz. With such a telescope, some of the major questions of our time can be addressed. What are dark energy and dark matter? What is the origin of the observed structure in the Universe? How did planets like the Earth form? The location and timing of the meeting are deliberate; October 4th 2007 will be the 50th anniversary of the lunch of Sputnik I and the radar detection of the Sputnik launch rocket by the 76-m (250-ft) Lovell telescope at Jodrell Bank Observatory. This meeting will therefore also celebrate 50 years of the Space Age and the Lovell telescope with a review of the modern state of radio astronomy and the new horizons that the SKA will open.

Confirmed invited speakers include: Chris Carilli (USA), Jim Cordes (USA), Thiebault Damour (France), Andrea Ferrara (Italy), Bryan Gaensler (Australia), Guido Garay (Chile), Micheal Kramer (UK), Steve Rawlings (UK), Frank Shu (Taiwan) and Kandu Subramanian (India).

In addition to invited talks, contributed papers (oral or poster) can be presented. The SOC will select a limited number of contributions for oral presentation on the basis of the submitted abstracts. The details of the full program will be published near to the conference date.

Deadlines

- November 2006: First announcement
- January 2007: Second announcement; Registration open
- June 2007: Third and Final announcement
- July 1, 2007: Registration and Abstract submission deadline
- August 1, 2007: Final Conference Programme
- October 1, 2007: Conference Starts
- October 5, 2007: Conference Ends

If you are interested in receiving further announcements, please send an email to majordomo@jb.man.ac.uk. with ”subscribe mru2007" in the body of the message. Registration and abstract submission will be available in early 2007 and will be announced on the webpage and via a second email. The size of this conference is strictly limited by the conference venue to ~200 delegates. Only full registration will guarantee attendance to the conference, so we urge all interested people to register early next year. Registration will open in early 2007. This will be advertised in the next announcement and on the webpage.

Webpage: http://www.jb.man.ac.uk/mru2007/
Email: mru2007@jb.man.ac.uk

FIRST INTERNATIONAL COLLOQUIUM ON SCIENTIFIC AND FUNDAMENTAL ASPECTS OF THE GALILEO PROGRAMME

Toulouse, France, 2 - 4 October 2007

Four organisations, namely Académie Nationale de l’Air et de l’Espace (ANAE), Bureau des Longitudes, Académie de Marine and the European Space Agency (ESA) are the main instigators of this colloquium meant to contribute to the 50th anniversary celebrations of the launch of Sputnik.

Topics

The colloquium will address three major topics:

- The fundamental aspects of navigation by satellites and Galileo: geodetic and temporal reference frames, relativistic frame, on board and ground clocks, orbits, radiative environment in orbit, inter-satellite links, fundamental aspects of propagation, tropospheric and ionospheric corrections, calibration and validation, relations with international organisations (BIPM, IGS).
- Scientific applications in meteorology, geodesy, geophysics, space physics, oceanography, land surface and ecosystem studies, using either normal or reflected signals, differential measurements, phase measurements, occultations, in real or delayed modes, using receivers placed on the ground, in airplanes or in scientific satellites.
- Scientific developments in physics and dealing with future systems, particularly in testing fundamental laws, in astronomy, in quantum communication, and in developing clocks or experiments based on GNSS.

This colloquium intends to bring together leading members of the international scientific community and their international partners. One of its aims is to propose to Galileo partners means of enhancing the scientific use of Galileo and to contribute to GNSS development based on scientific approaches.

Contact

Organisation Committee: Martine.Segur@anae.fr
Scientific Committee: Clovis.de.Matos@esa.int
URL: http://www.congrex.nl/07a06/

METAMATERIALS ‘2007

THE FIRST INTERNATIONAL CONGRESS ON ADVANCED ELECTROMAGNETIC MATERIALS FOR MICROWAVES AND OPTICS

Rome, Italy, 22 - 26 October 2007

The First International Congress on Advanced Electromagnetic Materials in Microwaves and Optics will be held in Rome, Italy, October 22-26, 2007. The congress, initiated by the European Network of Excellence “Metamorphose,” will provide a forum for the latest efforts in metamaterial research in Europe and worldwide. It will bring together the microwave, material science, and optical communities working in the field of artificial electromagnetic materials.

Topics

The Congress sessions will include invited plenary and focused session talks, oral presentations, interactive poster forums, tutorials and short courses, and the European Doctoral School on Metamaterials. The congress will aim to address a wide area of research related to metamaterials, artificial electromagnetic materials and surfaces in the microwave and optical ranges, encompassing general theory, design, applications, fabrication, and measurements. Special sessions will be devoted to applications of innovative materials, micro- and nanotechnologies, new physical phenomena in wireless and optical communication systems, high-speed circuits, optical sensing, nanoscale imaging, and photolithography. For full details of the congress scope and topics, visit the Web site:

http://www.metamorphose-eu.org/Congress/

Summaries should be submitted by uploading a PDF file to the congress Web site. The summary should be in English, typed single spaced, and should be no longer than two pages including figures and references. The summary should contain an abstract, a brief conclusion, and should clearly state the novelty of the presented work. The paper title, author's name, affiliation, and full address (including phone number and e-mail) must be provided in the beginning. Contact details of the authors will be required at the Congress Web site when uploading the summary. Only electronic submissions via the Web portal will be accepted. For detailed information on the paper-submission and summary templates, visit the congress Web site.

Deadlines

- Submission deadline: 5 February 2007
- Acceptance notification: 12 March 2007
- Final paper: 30 April 2007
- Congress: 22-26 October 2007

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URSI CONFERENCE CALENDAR

An up-to-date version of this Conference Calendar, with links to various conference web sites can be found at www.ursi.org/Calandar of supported meetings

December 2006

MST 11 - International Workshop on Technical and Scientific Aspects of MST Radar
Gadanki/Tirupati, India, 11-15 December 2006
cf. Announcement in the Radio Science Bulletin of March 2006, p. 54-55.
Contact : Prof. D. Narayana Rao, Director, National Atmospheric Research Laboratory, Post Box 123, Tirupati-517 502, India, Fax : +91 8585 272018/272021, E-mail : mst11@narl.gov.in , Web : http://www.narl.gov.in/mst-11.html

APMC 2006 - 2006 Asia-Pacific Microwave Conference
Yokohama, Japan, 12-15 December 2006
cf. Announcement in the Radio Science Bulletin of September 2005 p. 44
Contact : Dr. Takashi Ohira, 2-2-2 Hikaridai, Keihanna Science City, Kyoto 619-0288, Japan, Fax : +81 774-95 15 08, E-mail : ohira@atr.jp , Web : http://www.apmc2006.org

ICMARS-2006 - 3rd International Conference on Microwaves, Antenna, Propagation and Remote Sensing
Jodhpur, India, 20 -22 December 2006
cf. Announcement in the Radio Science Bulletin of September 2006, p. 49-50.
Contact : Prof O.P.N. Calla, ICRS, "OMNIWAS" A-23 Shatri Nagar, Jodhpur, Rajasthan, 342003, India, Phone : 0291-2613123, Fax : 0291-2626166, E-mail : opncalla@yahoo.co.in, Web : http://www.radioscience.org, http://www.icrsju.org

February 2007

ISSS8 - International School for Space Simulations
25 February - 3 March 2007
Contact : Prof. M. Ashour-Abdalla, IGPP/UCLA, Los Angeles, CA, 90095-1567 USA, Fax: (310) 206-3051, E-mail: mabdalla@igpp.ucla.edu , registration form , abstract form ,Web : http://www.isss8.ucla.edu/

March 2007

Telecom & JFMMA
Fes, Morocco, 14-16 March 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 75
Contact in France : Pr. A. MAMOUNI , IEMN CNRS, Cité scientifique, Av. Poincaré, BP 60069, 59652 Villeneuve d'Ascq Cédex, France , Email: ahmed.mamouni@iemn.univ-lille1.fr , Tél.: +33 (0) 3 20 19 79 39 , Fax.: 33 (0) 3 20 19 78 80 ;
Contact in Morocco : Pr. M. EL BEKKALI et Pr. A. BENBASSOU , Ecole Supérieure de Technologie de Fès , Route D'Immouzer - BP: 2427 – 30000 Fès - MAROC , Tél.: +212 (0) 35 60 05 85/86 , Fax: + 212 (0) 35 60 05 88,

E mail: moulhime.el.bekkali@caramail.com , ali.benbassou@caramail.com ,moulhime_el_bekkali@hotmail.com, Web : http://www.est-usmba.ac.ma/telecom2007/

April 2007

URBAN 2007 - Urban Remote Sensing Joint Event 2007
Paris, France, 11-13 April 2007
cf. announcement in the Radio Science Bulletin of June 2006, p. 66.
Contact : Paolo Gamba, Dipartimento di Elettronica, Università di Pavia, Via Ferrata 1, 27100 Pavia, Italy, Fax +390 382-422583, e-mail : paolo.gamba@unipv.it , Web : http://tlc.unipv.it/urban-remote-sensing-2007/index.html

Astrophysics in the LOFAR era
Emmen, the Netherlands, 23-27 April 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 76
Contact : Richard Strom, ASTRON, P.O. Box 2, NL-7990 AA Dwingeloo, the Netherlands, fax +31 521-595101, e-mail : secretary@lofar.org, workshop@lofar.org, Web : http://www.lofar.org/workshop/general.php

May 2007

12th Microcoll - Colloquium on Microwave Communications
Budapest, Hungary, 14-16 May 2007
Contact : Prof. L. Nagy, BUTE, Dept. of Broadband Communications, H-1111 Goldmann Gy. tér 3, Budapest, Hungary, fax +36 1-463 3289, E-mail : nagy@mht.bme.hu, Web : http://www.diamond-congress.hu/mow2007

June 2007

EMC Workshop 2007
Paris, France, 14-15 June 2007
Contact : Prof. Martine Liénard, Université de Lille, USTL, TELICE/IEMN - Bat. P3, 59655 Villeneuve d'Ascq Cedex, FRANCE, Phone: + 33 (0)3 20 33 71 34, Fax: + 33 (0)3 20 33 72 07, e-mail : emcworkshop@univ-lille1.fr, Web : http://emcworkshop.univ-lille1.fr/

EMC'07 - International Symposium on Electromagnetic Compatibility and EM Ecology
St. Petersburg, Russia, 26-29 June 2007
cf. Announcement in the Radio Science Bulletin of September 2006, p. 50.
Contact : Discone-Centre Ltd., St. Petersburg State Electrotechnical University - LETI, Tel. +7 812-234-4840, Fax +7 812-234-4681, E-mail : discone@mail.wplus.net , Web : www.eltech.ru/emc

July 2007

IRI/COST296 Workshop on Ionosphere Modeling, Forcing and Telecommunications
Prague, Czech Republic, 10-14 July 2007
Contact : Dr. Jan Lastovicka, Institute of Atmospheric Physics, Acad. Sci. Czech Republic, Bocni II, 1401a, 14131 Prague 4, Czech Republic, Fax +420 2727 63745, jla@ufa.cas.cz

URSI CNC/USNC North American Radio Science Meeting
Ottawa, ON, Canada, 22-26 July 2007
Contact : Dr. Yahia M.M. Antar, (CNC Chair), Email: antar-y@rmc.ca , Dr. George Uslenghi, (USNC Chair), Email: uslenghi@uic.edu, Web : http://ursi2007.ee.umanitoba.ca

EMTS 2007 - URSI Commission B EMT-Symposium
Ottawa, ON, Canada, 26-28 July 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 77.
Contact : Prof. Lot Shafai, Chair Commission B, Dept. of Electrical and Computer Engineering, University of Manitoba, 75 Chancellors Circle, Winnipeg, MB, Canada R3T 5V6, Fax (204) 269 - 0381, E-mail : shafai@ee.umanitoba.ca , Web : http://emts2007.ee.umanitoba.ca

International Symposium on Signals, Systems, and Electronics (ISSSE 2007)
Montreal, Canada, 30 July - 2 August 2007
cf. Announcement in the Radio Science Bulletin of December 2006, 78.
Contact: Prof. Ke Wu, Director of Poly-Grames Research Center, Ecole Polytechnique, C. P. 6079, Succ. Centre-Ville, Montreal, Quebec, Canada H3C 3A7, Tel: +1 (514) 340-4711 ext. 5991, Fax: +1 (514) 340-5892, E-mail: ke.wu@polymtl.ca or ke.wu@ieee.org

August 2007

Rarotonga Energetic Particle Workshop 2007
Rarotonga (Cook Islands), 5-10 August 2007
Contact : Dr. Craig J. Rodger, Department of Physics, University of Otago, P.O. Box 56, Dunedin, New Zealand, Fax +64 3 479 0964, crodger@physics.otago.ac.nz , Web : http://www.physics.otago.ac.nz/space/REPW2007_Home_Page.htm

ISAP 2007 - International Symposium on Antennas and Propagation
Niigata, Japan, 20-24 August 2007
Contact : Yoshihiko Konishi (Publicity Chair), Mitsubishi Electric Corporation, 5-1-1 Ofuna, Kamakura, 247-8501

Japan, E-mail : isap-2007@mail.ieice.org, Web : http://www.isap07.org

September 2007

International Symposium on Radio Systems and Space Plasma
Borovets, Bulgaria, on 2-5 September 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 79
Contact : Prof. B. Shishkov, Head of Telecommunication Dept., Institute of Mathematics & Informatics, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 8, Sofia 1113, Bulgaria, fax: ++359 2 971 3649, e-mail: bshishkov@math.bas.bg, Web : http://www.math.bas.bg/isrssp/

AP-RASC 2007 - Asia-Pacific Radio Science Conference
Perth, Western Australia, 17-20 September 2007
Contact : Dr. Phil Wilkinson, Deputy Director IPS Radio and Space Services, Department of Industry, Tourism and Resources, P O Box 1386, Haymarket, NSW 1240, AUSTRALIA, Tel : +61 2 9213 8003, Fax : +61 2 9213 8060, E-mail: phil@ips.gov.au, Web : http://www.ap-rasc07.org/

International Conference on Electromagnetics in Advanced Applications (ICEAA 07)
Torino, Italy, 17 - 21 September 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 79.
Contact: Prof. Roberto D. Graglia, Chair of ICEAA Organizing Committee, Dipartimento di Elettronica, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy, E-mail: roberto.graglia@polito.it or Prof. Piergiorgio L. E. Uslenghi, Chair of ICEAA Scientific Committee, Department of ECE (MC 154), University of Illinois at Chicago, 851 South Morgan Street, Chicago, IL 60607, USA, E-mail: uslenghi@uic.edu.

EMC Zürich 2007
München, Germany, 24-28 September 2007
Contact : Prof. Dr. P. Russer, Symposium President, TU Munich, Germany and Prof. Dr. R. Vahldieck, General Chairman, ETH Zürich, IFH, Switzerland, Tel: +41 44 632 2951, Fax: +41 44 632 1198 , e-mail: info@emczurich.ethz.ch , http://www.emc-zurich.ch/

October 2007

From Planets to Dark Energy: the Modern Radio Universe
Manchester, UK, 1-5 October 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 80.
Contact : Prof. Ph. Diamond, Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK, fax +44 1477-572618, E-mail : pdiamond@jb.man.ac.uk , majordomo@jb.man.ac.uk , Web : http://www.jb.man.ac.uk/mru2007/

Scientific and Fundamental Aspects of the Galileo Programme
Toulouse, France, 2-4 October 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 81
Contact : Dr. Bertram Arbesser-Rastburg, ESA-ESTEC, TEC-EEP, Postbus 299, NL-2200 AG Noordwijk, the Netherlands, fax +31 71 565-4999, Organisation Committee: Martine.Segur@anae.fr, Scientific Committee: Clovis.de.Matos@esa.int, Web : www.congrex.nl/07a06

Metamaterials 2007 - The First International Congress on Advanced Electromagnetic Materials for Microwaves and Optics
Rome, Italy, 22-26 October 2007
cf. Announcement in the Radio Science Bulletin of December 2006, p. 81.
Contact : Dr. Said Zouhdi, Electrical Engineering, University Pierre et Marie Curie, Paris, France + Laboratoire de Genie Electrique de Paris LGEP-Supelec, Fax : + 33 1 69 41 83 18, E-mail : sz@ccr.jussieu.fr

December 2007

APMC 2007 - 2007 Asia-Pacific Microwave Conference
Bangkok, Thailand, 11-14 December 2007
cf. Announcement in the Radio Science BUlletin of September 2006, p. 51.
Contact : Dr. Chuwong Phongcharoenpanich, General Secretary of APMC 2007, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand, E-mail:kpchuwon@kmitl.ac.th, Web:http://www.apmc2007.org/

July 2008

EUROEM 2008 - European Electromagnetics
Lausanne, Switzerland, 21-25 July 2008
Contact : EUROEM'08, EPFL-STI- LRE, Station 11, CH-1015 Lausanne, Switzerland, Tel : +41-21-693 26 20, Fax : +41-21-693 46 62, E-mail: information@euroem.org, Web : http://www.euroem.org

August 2008

URSI GA08 - XXIXth URSI General Assembly
Chicago, IL, USA, 9-16 August 2008
Contact : URSI Secretariat, c/o INTEC, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium, Tel. : +32 9 264 3320, Fax : +32 9 264 4288, E-mail : info@ursi.org

News from the URSI Community

BOOK PUBLISHED BY AN URSI RADIOSCIENTIST

CDMA Radio with Repeaters

Series: Information Technology: Transmission, Processing and Storage

By Joseph Shapira and Shmuel Miller, Springer, 2007, XXIV, 425 p., 221 illus., Hardcover,
ISBN-10: 0-387-26329-2, ISBN-13: 978-0-387-26329-8

About this book

The book is written for RF network engineers and cellular networks managers and addresses the role of repeaters in the CDMA network, their interaction with the network and the needed integrative design and optimization of the repeater-embedded network. The approach of the book is to develop functional comprehension of the complex radio network, and affinity to the factors dominating the Radio Resource Utilization. Simple models are developed, recognizing that over-complex models and simulations lack the clarity of the underlying processes while failing to match the measured performance anyhow. Field-measured case studies complement the analysis, and methodology for use of dynamically measured network parameters in tuning and optimizing the network is laid out.

Table of contents

Introduction and Preview.- CDMA Air Interface Overview.- The Mobile Radio Propagation Channel.- Radio Access Related Performance of CDMA Cellular Networks.- Diversity in Transmission and Reception.- Repeaters Design and Tuning in CDMA Networks.- Backhaul for RF Distributed Radio Access Nodes.- Repeater Economics.- Advances in CDMA Repeaters.- Appendix A: Reverse Link Interference in Hetereogeneous Cell Clusters.- Appendix B: Evaluation of the Power Rise Equation.- Appendix C: Orthogonality Factor Through Cell.- Appendix D: System Noise and Dynamic Range.- Appendix E: Envelope Correlation and Power Correlation in Fading Channels.- Appendix F: Eigenvalue Analysis of MRC.- Optimal Sector Beamwidth.- Appendix H: Cellular Bands and Frequency Allocations.

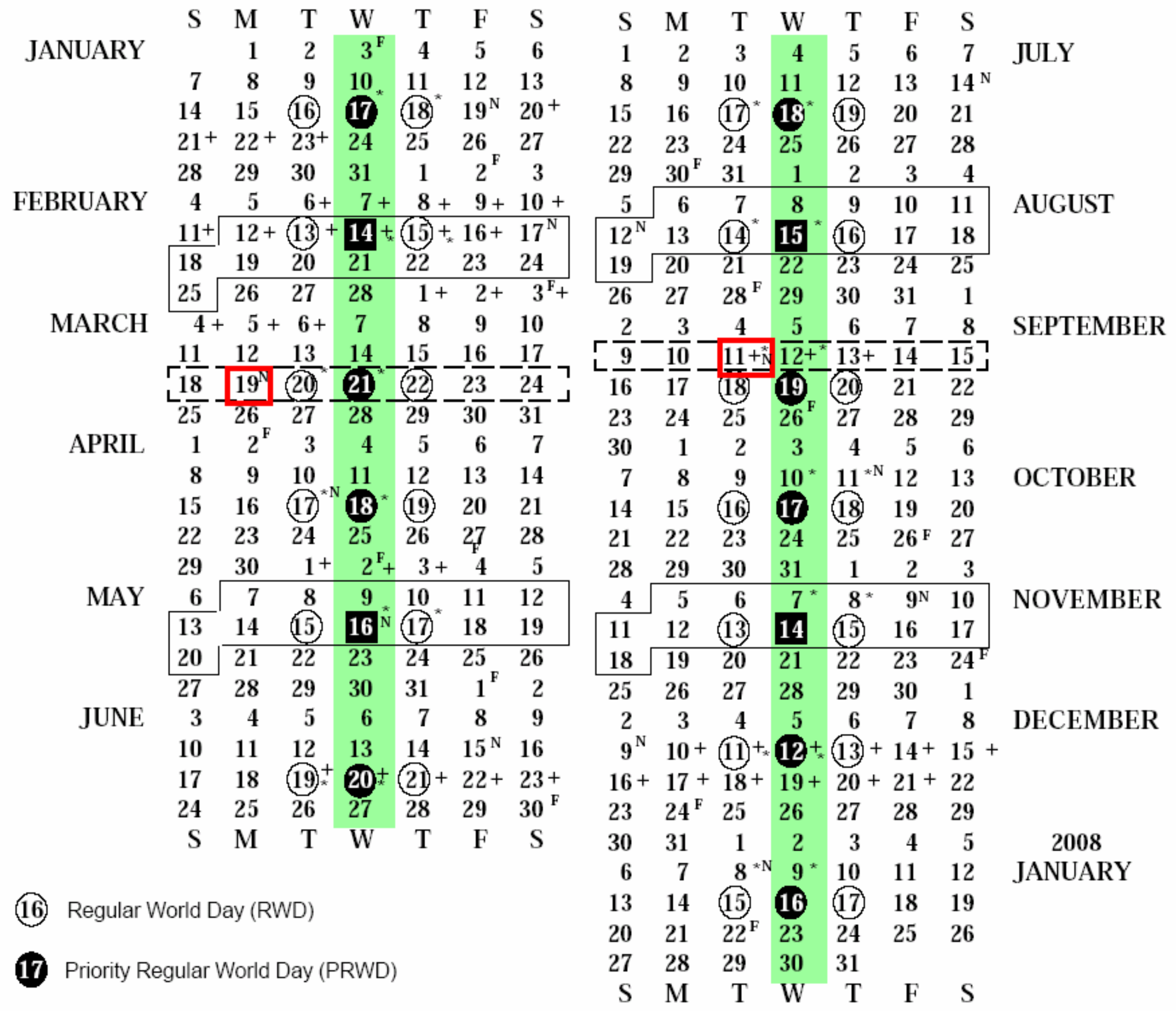
About the authors

Dr. Joseph Shapira is working at the Indian Institute of Technology Madras/ Comm&Sens, 23 Sweden Street, 34980 Haifa, Israel. He was an URSI Board member from 1996 until 2002.

We do not have any information on Mr. Shmuel Miller.

This book is available from December 17, 2006 onwards.

International Geophysical Calendar 2007



	S	M	T	W	T	F	S
JANUARY		1	2	3^{F}	4	5	6
	7	8	9	10	11	12	13
	14	15	16	17*	18*	19^{N}	20+
	21+	22+	23+	24	25	26	27
	28	29	30	31	1	2^{F}	3
FEBRUARY	4	5	6+	7+	8+	9+	10+
	11+	12+	13+	14+*	15+*	16+	17^{N}
	18	19	20	21	22	23	24
	25	26	27	28	1+	2+	3^{F}+
MARCH	4+	5+	6+	7	8	9	10
	11	12	13	14	15	16	17
	18	19^{N}	20*	21*	22	23	24
	25	26	27	28	29	30	31
APRIL	1	2^{F}	3	4	5	6	7
	8	9	10	11	12	13	14
	15	16	17*N	18*	19	20	21
	22	23	24	25	26	27^{F}	28
	29	30	1+	2^{F}+	3+	4	5
MAY	6	7	8	9	10	11	12
	13	14	15	16*N	17*	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31	1^{F}	2
JUNE	3	4	5	6	7	8	9
	10	11	12	13	14	15^{N}	16
	17	18	19+*	20+*	21+	22+	23+
	24	25	26	27	28	29	30^{F}
	S	M	T	W	T	F	S

S	M	T	W	T	F	S	
1	2	3	4	5	6	7	JULY
8	9	10	11	12	13	14^{N}	
15	16	17*	18*	19	20	21	
22	23	24	25	26	27	28	
29	30^{F}	31	1	2	3	4	
5	6	7	8	9	10	11	AUGUST
12^{N}	13	14*	15*	16	17	18	
19	20	21	22	23	24	25	
26	27	28^{F}	29	30	31	1	
2	3	4	5	6	7	8	SEPTEMBER
9	10	11+*N	12+*	13+	14	15	
16	17	18	19	20	21	22	
23	24	25	26^{F}	27	28	29	
30	1	2	3	4	5	6	
7	8	9	10*	11*N	12	13	OCTOBER
14	15	16	17	18	19	20	
21	22	23	24	25	26^{F}	27	
28	29	30	31	1	2	3	
4	5	6	7*	8*	9^{N}	10	NOVEMBER
11	12	13	14	15	16	17	
18	19	20	21	22	23	24^{F}	
25	26	27	28	29	30	1	
2	3	4	5	6	7	8	DECEMBER
9^{N}	10+	11+*	12+*	13+	14+	15+	
16+	17+	18+	19+	20+	21+	22	
23	24^{F}	25	26	27	28	29	
30	31	1	2	3	4	5	2008
6	7	8*N	9*	10	11	12	JANUARY
13	14	15	16	17	18	19	
20	21	22^{F}	23	24	25	26	
27	28	29	30	31			
S	M	T	W	T	F	S	

⑯ Regular World Day (RWD)

⓱ Priority Regular World Day (PRWD)

■ 14 Quarterly World Day (QWD) also a PRWD and RWD

🟩 3 Regular Geophysical Day (RGD)

12 13 World Geophysical Interval (WGI)

+ Incoherent Scatter Coordinated Observation Day

N NEW MOON F FULL MOON

🟥 19 Day of Solar Eclipse: Mar 19 and Sep 11

18 19 Airglow and Aurora Period

17* Dark Moon Geophysical Day (DMGD)

This Calendar continues the series begun for the IGY years 1957-58, and is issued annually to recommend dates for solar and geophysical observations, which cannot be carried out continuously. Thus, the amount of observational data in existence tends to be larger on Calendar days. The recommendations on data reduction and especially the flow of data to World Data Centers (WDCs) in many instances emphasize Calendar days. The Calendar is prepared by the International Space Environment Service (ISES) with the advice of spokesmen for the various scientific disciplines. For some programs, greater detail concerning recommendations appears from time to time published in IAGA News, IUGG Chronicle, URSI Information Bulletin and other scientific journals or newsletters. For on-line information, see **http://www.ises-spaceweather.org.**

The definitions of the designated days remain as described on previous Calendars. Universal Time (UT) is the standard time for all world days. Regular Geophysical Days (RGD) are each Wednesday. Regular World Days (RWD) are three consecutive days each month (always Tuesday, Wednesday and Thursday near the middle of the month). Priority Regular World Days (PRWD) are the RWD which fall on Wednesdays. Quarterly World Days (QWD) are one day each quarter and are the PRWD which fall in the World Geophysical Intervals (WGI). The WGI are fourteen consecutive days in each season, beginning on Monday of the selected month, and normally shift from year to year. In 2007 the WGI are February, May, August and November.

2007 Solar Eclipses:

The only solar eclipses in 2007 will be partial; no total or annular solar eclipses will occur.

a) 19 March 2007 (partial) eclipse will peak at 2:32 UT, with a maximum of 87% coverage of the sun by the moon. Over 80% of the sun will be covered from northwestern Russia and 60% from Iran, Afghanistan, Pakistan, Northern India, northwestern China, western Mongolia and western Russia. Thailand, Cambodia, Vietnam, eastern China, and southeastern and northeastern Japan are barely within the zone of partial eclipse.

b) 11 September 2007 (partial) eclipse visible only from South America and the part of Antarctica facing that continent, with maximum coverage of 75%. The farther south, the greater the eclipse, extending up to almost 60% in Patagonia, 50% in Buenos Aires, and almost 40% in Rio de Janeiro.

2007 Lunar eclipses:

a) March 3, 2007, total lunar eclipse will be visible throughout Europe, Africa, and western Asia. The moon will rise eclipsed throughout North and South America, except for Alaska, and the moon will set eclipsed throughout the rest of Asia and Australia except for easternmost Australia.

b) August 28, 2007, total lunar eclipse will be entirely visible in eastern Australia, New Zealand, Hawaii, and Alaska. The moon will set eclipsed throughout the rest of North America and in South America, and the moon will rise eclipsed in eastern Asia. No part of the eclipse will be visible form Europe or Africa.

Information provided by Jay M. Pasachoff on behalf of the Working Group on Eclipses of the International Astronomical Union based on maps by Fred Espenak, NASA's Goddard Space Flight Center. See http://www.totalsolareclipse.net and http://sunearth.gsfc.nasa.gov/eclipse/OH/OH2007.html. See also the IAU Program Group on Public Education at the Times of Eclipses site: http://www.eclipses.info.

Eclipse References:

- Fred Espenak, Fifty Year Canon of Solar Eclipses: 1986-2035, NASA Reference Publication 1178 Revised, July 1987.
- Leon Golub and Jay M. Pasachoff, The Solar Corona, Cambridge University Press, 1998. http://www.williams.edu/Astronomy/corona
- Jay M. Pasachoff and Alex Filippenko, The Cosmos: Astronomy in the New Millennium, Brooks/Cole Publishers, 2004. http://info.brookscole.com/pasachoff Brooks/Cole Publishing, 2002. http://www.williams.edu/Astronomy/jay
- Leon Golub and Jay M. Pasachoff, Nearest Star: The Exciting Science of Our Sun, Harvard University Press, 2001. http://www.williams.edu/astronomy/neareststar
- Jay M. Pasachoff, The Complete Idiot's Guide to the Sun, Alpha Books, 2003 http://www.williams.edu/astronomy/sun]

Meteor Showers (selected by P. Jenniskens, SETI Institute, Mountain View, CA, pjenniskens@mail.arc.nasa.gov):

a) Meteor outbursts are unusual showers (often of short duration) from the crossing of relatively recent comet ejecta. Dates for year 2007:

- Apr 28, 17:28 UT, alpha-Bootids (RA = 219º, Decl. = +19º): possible encounter with 1-revolution (1-rev) dust trail of unknown parent comet;
- Aug 12, 22:42 UT, Perseids: encounter with the 1479-dust trail of 109P/Swift-Tuttle; Aug 13, about 04h UT: possible encounter with older Filament debris of 109P/Swift-Tuttle;
- Sep 1, 11:37 UT: Aurigids (RA = 90º, Decl. = +39º) outburst (possible storm) from 1-rev trail of comet C/1911 N1 (Kiess);
- Nov 18, 23:03 UT, Leonids: encounter with the 1932 dust (2-rev) ejecta of comet 55P/Tempel-Tuttle; also possible older Filament encounter at about Nov 19 00:19 UT.
- Dec 21, 03:40 UT: alpha-Lyncids (RA = 138º, Decl. = +44º): possible encounter with 1-revolution dust trail of unknown parent comet;
- Dec 22, about 20h UT, Ursids: possible outburst from Filament of comet 8P/Tuttle.

b) Regular meteor showers: The dates (based on UT in year 2007) for regular meteor showers are: Jan 1-6, peak Jan 04 03:22 UT (Quadrantids); Apr 16-25, peak Apr 23 01h UT (Lyrids); Apr 19-May 28, peak May 05 09h UT, broad component peaks at May 07 23h UT (Eta-Aquariids); May 22-July 02, peak Jun 07 23h UT (Daytime Arietids); May 20-July 05, peak Jun 09 22h UT (Daytime Zeta-

Perseids); Jun 05-July 17, peak Jun 28 21h (Daytime Beta-Taurids); Jul 8-Aug 19, peak Jul 29 04h UT (S. Delta-Aquariids); Jul 17-Aug 24, peak Aug 13 09:57 UT (Perseids); Sep 26-Oct 03, peak Oct 02 01h UT (Daytime Sextantids); Oct 02-Nov 07, peak Oct 22 12h UT, bright meteors peak at Oct 18 09h UT (Orionids); Oct 31-Nov 23, peak Nov 17 23h UT (Leonids); Nov 27-Dec 18, peak Dec 14 13:56 UT (Geminids); Dec 17-26, peak at Dec 23 08h UT 2007 (Ursids).

Meteor Shower Websites:

- Shower activity forecast for given location (Peter Jenniskens): http://leonid.arc.nasa.gov/estimator.html
- International Meteor Organization: http://www.imo.net
- Institut de Mécanique céleste et de calcul des éphémérides: http://www.imcce.fr/page.php?nav=en/ephemerides/phenomenes/meteor/index.php

References:

Peter Jenniskens, Meteor showers and their parent comets. Cambridge University Press, 2006.

The occurrence of **unusual solar or geophysical conditions** is announced or forecast by the ISES through various types of geophysical **"Alerts"** (which are widely distributed by telegram and radio broadcast on a current schedule). Stratospheric warmings (STRATWARM) are also designated. The meteorological telecommunications network coordinated by WMO carries these worldwide Alerts once daily soon after 0400 UT. For definitions of Alerts see ISES "Synoptic Codes for Solar and Geophysical Data", March 1990 and its amendments (http://ises-spaceweather.org). Retrospective World Intervals are selected and announced by MONSEE and elsewhere to provide additional analyzed data for particular events studied in the ICSU Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) programs.

Recommended Scientific Programs (Final Edition): The following material was reviewed in 2006 by spokesmen of IAGA, WMO and URSI as suitable for coordinated geophysical programs in 2007.)

- **Airglow and Aurora Phenomena**. Airglow and auroral observatories operate with their full capacity around the New Moon periods. However, for progress in understanding the mechanism of many phenomena, such as low latitude aurora, the coordinated use of all available techniques, optical and radio, from the ground and in space is required. Thus, for the airglow and aurora 7-day periods on the Calendar, ionosonde, incoherent scatter, special satellite or balloon observations, etc., are especially encouraged. Periods of approximately one weeks' duration centered on the New Moon are proposed for high resolution of ionospheric, auroral and magnetospheric observations at high latitudes during northern winter.
- **Atmospheric Electricity.** Non-continuous measurements and data reduction for continuous measurements of atmospheric electric current density, field, conductivities, space charges, ion number densities, ionosphere potentials, condensation nuclei, etc.; both at ground as well as with radiosondes, aircraft, rockets; should be done with first priority on the RGD each Wednesday, beginning on 3 January 2007 at 0000 UT, 10 January at 0600 UT, 17 January at 1200 UT, 24 January at 1800 UT, etc. (beginning hour shifts six hours each week, but is always on Wednesday). Minimum program is at the same time on PRWD beginning with 17 January at 1200 UT. Data reduction for continuous measurements should be extended, if possible, to cover at least the full RGD including, in addition, at least 6 hours prior to indicated beginning time. Measurements prohibited by bad weather should be done 24 hours later. Results on sferics and ELF are wanted with first priority for the same hours, short-period measurements centered around the minutes 35-50 of the hours indicated. Priority Weeks are the weeks that contain a PRWD; minimum priority weeks are the ones with a QWD. The World Data Centre for Atmospheric Electricity, 7 Karbysheva, St. Petersburg 194018, USSR, is the collection point for data and information on measurements.
- **Geomagnetic Phenomena.** It has always been a leading principle for geomagnetic observatories that operations should be as continuous as possible and the great majority of stations undertake the same program without regard to the Calendar.

  Stations equipped for making magnetic observations, but which cannot carry out such observations and reductions on a continuous schedule are encouraged to carry out such work at least on RWD (and during times of MAGSTORM Alert).
- **Ionospheric Phenomena.** Special attention is continuing on particular events that cannot be forecast in advance with reasonable certainty. These will be identified by Retrospective World Intervals. The importance of obtaining full observational coverage is therefore stressed even if it is possible to analyze the detailed data only for the chosen events. In the case of vertical incidence sounding, the need to obtain quarter-hourly ionograms at as many stations as possible is particularly stressed and takes priority over recommendation (a) below when both are not practical.
- For the **vertical incidence (VI) sounding program**, the summary recommendations are:

(a) All stations should make soundings on the hour and every quarter hour;

(b) On RWDs, ionogram soundings should be made at least every quarter hour and preferably every five minutes or more frequently, particularly at high latitudes;

(c) All stations are encouraged to make f-plots on RWDs; f-plots should be made for high latitude stations, and for so-called "representative" stations at lower latitudes for all days (i.e., including RWDs and WGIs) (Continuous records of ionospheric parameters are acceptable in place of f-plots at temperate and low latitude stations);

(d) Copies of all ionogram scaled parameters, in digital form if possible, be sent to WDCs; (e) Stations in the eclipse zone and its conjugate area should take continuous observations on solar eclipse days and special observations on adjacent days. See also recommendations under Airglow and Aurora Phenomena.

- For the **incoherent scatter observation program**, every effort should be made to obtain measurements at least on the Incoherent Scatter Coordinated Observation Days, and intensive series should be attempted whenever possible in WGIs, on Dark Moon Geophysical Days (DMGD) or the Airglow and Aurora Periods. The need for collateral VI observations with not more than quarter-hourly spacing at least during all observation periods is stressed.

  Special programs include:

  CAWSES – Climate and Weather of the Sun-Earth System, (S. Basu – sbasu@cawses.bu.edu);

  CEDAR — Coupling, Energetics & Dynamics of Atmospheric Regions (http://cedarweb.hao.ucar.edu/);

  GEM – Geospace Environment Modeling (http://www-ssc.igpp.ucla.edu/gem/);

  MST – Studies of the Mesosphere, Stratosphere, and Troposphere — Coordinated D- and E-region campaigns focusing on lower altitudes, with JRO in high resolution MST mode – gravity wave momentum fluxes (G. Lehmacher – glehmac@clemson.edu);

  Stratospheric Warmings = Dynamics and temperature of the lower thermosphere during sudden stratospheric warming – ten days of observation for each period in February and December (L. Goncharenko — lpg@haystack.mit.edu);

  Synoptic – Wide coverage of the F-region, augmented with topside or E-region measurements – broad latitudinal coverage (W. Swartz – wes@ece.cornell.edu).

  TEC Mapping = ISR/GPS Coordinated Observation of Electron Density Variations (Shun-Rong Zhang — shunrong@haystack.mit.edu);

  TIDs = Latitude dependence of the F-Region plasma variations during the passage of large- and medium-scale Traveling Ionospheric Disturbances (TIDs) — (T. Tsugawa — tsugawa@stelab.nagoya-u.ac.jp)

  IPY = **International Polar Year-long observations with the EISCAT Svalbard Incoherent Scatter Radar (ISR)** to provide an unprecedented data set with multiple applications and to provide correlative data for other instrumentation and models committed to the IPY. (Tony.van.Eyken@eiscat.se — https://e7.eiscat.se/groups/IPY).

  AO —Arecibo Obs (**http://www.naic.edu/aisr/olmon2/omframedoc.html**);

  JRO – Jicamarca Radio Observatory (**http://jro.igp.gob.pe/english/radar/operation/real-time_en.php**).

Special programs: Dr. Wesley E. Swartz, 316 Rhodes Hall, School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA. Tel. 607-255-7120; Fax 607-255-6236; e-mail: wes@ece.cornell.edu; URSI Working Group G.5. See http://people.ece.cornell.edu/wes/URSI_ISWG/2007WDschedule.htm for complete 2007 definitions.

- For the **ionospheric drift or wind measurement** by the various radio techniques, observations are recommended to be concentrated on the weeks including RWDs.
- For **traveling ionosphere disturbances**, propose special periods for coordinated measurements of gravity waves induced by magnetospheric activity, probably on selected PRWD and RWD.
- For the **ionospheric absorption program** half-hourly observations are made at least on all RWDs and half-hourly tabulations sent to WDCs. Observations should be continuous on solar eclipse days for stations in eclipse zone and in its conjugate area. Special efforts should be made to obtain daily absorption measurements at temperate latitude stations during the period of Absorption Winter Anomaly, particularly on days of abnormally high or abnormally low absorption (approximately October-March, Northern Hemisphere; April-September, Southern Hemisphere).
- For **back-scatter and forward scatter programs**, observations should be made and analyzed at least on all RWDs.
- For **synoptic observations** of mesospheric (D region) electron densities, several groups have agreed on using the RGD for the hours around noon.
- For **ELF noise measurements** involving the earth-ionosphere cavity resonances any special effort should be concentrated during the WGIs.

It is recommended that more intensive observations in all programs be considered on days of unusual meteor activity.

- **Meteorology.** Particular efforts should be made to carry out an intensified program on the RGD — each Wednesday, UT. A desirable goal would be the scheduling of meteorological rocketsondes, ozone sondes and radiometer sondes on these days, together with maximum-altitude rawinsonde ascents at both 0000 and 1200 UT.
- During **WGI and STRATWARM Alert Intervals**, intensified programs are also desirable, preferably by the implementation of RGD-type programs (see above) on Mondays and Fridays, as well as on Wednesdays.
- **Global Atmosphere Watch (GAW).** The World Meteorological Organizations (WMO) GAW integrates many monitoring and research activities involving measurement of atmospheric composition. Serves as an early warning system to detect further changes in atmospheric concentrations of greenhouse gases, changes in the ozone layer and in the long range transport of pollutants, including acidity and toxicity of rain as well as of atmospheric burden of aerosols (dirt and dust particles). Contact WMO, 7 bis avenue de la Paix, P.O. Box 2300, 1211 Geneva, Switzerland.
- **Solar Phenomena.** Observatories making specialized studies of solar phenomena, particularly using new or complex techniques, such that continuous observation or reporting is impractical, are requested to make special efforts to provide to WDCs data for solar eclipse days, RWDs and during PROTON/FLARE ALERTS. The attention of those recording solar noise spectra, solar

magnetic fields and doing specialized optical studies is particularly drawn to this recommendation.

- **CAWSES (Climate and Weather of the Sun-Earth System).** Program within the SCOSTEP (Scientific Committee on Solar-Terrestrial Physics): 2004-2008. Its focus is to mobilize the community to fully utilize past, present, and future data; and to produce improvements in space weather forecasting, the design of space- and Earth-based technological systems, and understanding the role of solar-terrestrial influences on Global Change. Contact is Su. Basu (sbasu@bu.edu), Chair of CAWSES Science Steering Group. Program "theme" areas are: Solar Influence on Climate – M. Lockwood and L. Gray (UK); Space Weather: Science and Applications – J. Kozyra (USA) and K. Shibata (Japan); Atmospheric Coupling Processes – F. Luebken (Germany) and J. Alexander (USA); Space Climatology – C. Frolich (Switzerland) and J. Sojka (USA); and Capacity Building and Education, M.A. Geller (USA). See http://www.bu.edu/cawses/.
- **IHY (International Heliophysical Year) 2007** – International effort to advance our understanding of the fundamental heliophysical processes that govern the Sun, Earth, and Heliosphere — http://ihy2007.org/. See also the IPY (International Polar Year) — http://www.ipy.org/; IYPE (International Year of the Planet Earth) — http://www.yearofplanetearth.org/, and eGY (Electronic Geophysical Year 2007-2008) — http://www.egy.org/ — all celebrating the 50th Anniversary of the IGY (International Geophysical Year 1957-58) — http://www.nas.edu/history/igy/.
- **Space Research, Interplanetary Phenomena, Cosmic Rays, Aeronomy.** Experimenters should take into account that observational effort in other disciplines tends to be intensified on the days marked on the Calendar, and schedule balloon and rocket experiments accordingly if there are no other geophysical reasons for choice. In particular it is desirable to make rocket measurements of ionospheric characteristics on the same day at as many locations as possible; where feasible, experimenters should endeavor to launch rockets to monitor at least normal conditions on the Quarterly World Days (QWD) or on RWDs, since these are also days when there will be maximum support from ground observations. Also, special efforts should be made to assure recording of telemetry on QWD and Airglow and Aurora Periods of experiments on satellites and of experiments on spacecraft in orbit around the Sun.
- **Meteor showers.** Of particular interest are both predicted and unexpected showers from the encounter with recent dust ejecta of comets (meteor outbursts). The period of activity, level of activity, and magnitude distributions need to be determined in order to provide ground truth for comet dust ejection and meteoroid stream dynamics models. Individual orbits of meteoroids can also provide insight into the ejection circumstances. If a new (1-2 hour duration) shower is observed due to the crossing of the 1-revolution dust trail of a (yet unknown) Earth threatening long-period comet, observers should pay particular attention to a correct determination of the radiant and time of peak activity in order to facilitate predictions of future encounters. Observations of meteor outbursts should be reported to the I.A.U. Minor Planet Center (dgreen@cfa.harvard.edu) and International Meteor Organization (visual@imo.net). The activity curve, mean orbit, and particle size distribution of minor annual showers need to be characterised in order to understand their relationship to the dormant comets among near-Earth objects. Annual shower observations should be reported to national meteor organizations, or directly to the International Meteor Organization (http://www.imo.net). Meteoroid orbits are collected by the IAU Meteor Data Center (http://www.astro.sk/~ne/IAUMDC/Ph2003/).
- The **International Space Environment Service (ISES)** is a permanent scientific service of the International Union of Radio Science (URSI), with the participation of the International Astronomical Union and the International Union Geodesy and Geophysics. ISES adheres to the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) of the International Council of Scientific Unions (ICSU). The ISES coordinates the international aspects of the world days program and rapid data interchange.

This Calendar for 2007 has been drawn up by H.E. Coffey, of the ISES Steering Committee, in association with spokesmen for the various scientific disciplines in SCOSTEP, IAGA and URSI and other ICSU organizations. Similar Calendars are issued annually beginning with the IGY, 1957-58, and are published in various widely available scientific publications. PDF versions of the past calendars are available online at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/IGC_CALENDAR.

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Additional copies are available upon request to ISES Chairman, Dr. David Boteler, Geomagnetic Laboratory, Natural Resources Canada, 7 Observatory Crescent, Ottawa, Ontario, Canada, K1A 0Y3, FAX (613)824-9803, e-mail dboteler@NRCan.gc.ca, or ISES Secretary for World Days, Ms. H.E. Coffey, WDC for Solar-Terrestrial Physics, Boulder, NOAA E/GC2, 325 Broadway, Boulder, Colorado 80305, USA FAX number (303)497-6513; e-mail Helen.E.Coffey@noaa.gov.

The calendar is available on-line at http://www.ises-spaceweather.org.

NOTES on other dates and programs of interest:

1. Days with **significant meteor shower** activity (based on UT in year 2007) — regular meteor showers: Jan 1-6, peak Jan 04 0322 UT (Quadrantids); Apr 16-25, peak Apr 23 01h UT (Lyrids); Apr 19-May 28, peak May 05 09h UT, broad component peaks at May 07 23h UT (Eta-Aquariids); May 22-July 02, peak Jun 07 23h UT (Daytime Arietids); May 20-July 05, peak Jun 09 22h UT (Daytime Zeta-Perseids); Jun 05-July 17, peak Jun 28 21h (Daytime Beta-Taurids); Jul 8-Aug 19, peak Jul 29 04h UT (S. Delta-Aquariids); Jul 17-Aug 24, peak Aug 13 0957 UT (Perseids); Sep 26-Oct 03, peak Oct 02 01h UT (Daytime Sextantids); Oct 02-Nov 07, peak Oct 22 12h UT, bright meteors peak at Oct 18 09h UT (Orionids); Oct 31-Nov 23, peak Nov 17 23h UT (Leonids); Nov 27-Dec 18, peak Dec 14 1356 UT (Geminids); Dec 17-26, peak at Dec 23 08h UT 2007 (Ursids). **Meteor outbursts** are unusual showers (often of short duration) from the crossing of relatively recent comet ejecta. Dates for year 2007: Apr 28, 1728 UT; Aug 12, 2242 UT; Sep 1, 1137 UT; Nov 18, 2303 UT; Dec 21, 0340 UT; Dec 22, about 20h UT — see the long text for more information on these outbursts.

   These can be studied for their own geophysical effects or may be "geophysical noise" to other experiments.
2. **GAW (Global Atmosphere Watch)** — early warning system for changes in greenhouse gases, ozone layer, and long range transport of pollutants — http://www.wmo.ch/web/arep/gaw/gaw_home.html. (See Explanations.)
3. **CAWSES (Climate and Weather of the Sun-Earth System) —** SCOSTEP Program 2004-2008. Theme areas: Solar Influence on Climate; Space Weather: Science and Applications; Atmospheric Coupling Processes; Space Climatology; and Capacity Building and Education.http://www.bu.edu/cawses (See Explanations.) (S. Basu —sbasu@cawses.bu.edu)
4. **IHY (International Heliophysical Year) 2007 –** International effort to advance our understanding of the fundamental heliophysical processes that govern the Sun, Earth, and Heliosphere — http://ihy2007.org/. See also the IPY (International Polar Year) — http://www.ipy.org/;\ IYPE (International Year of the Planet Earth) — http://www.yearofplanetearth.org/, and eGY (Electronic Geophysical Year 2007-2008) — http://www.egy.org/ — all celebrating the 50th Anniversary of the IGY (International Geophysical Year 1957-58) http://www.nas.edu/history/igy/.
5. **+ Incoherent Scatter Coordinated Observations Days** (see Explanations) starting at 1300 UT on the first day of the intervals indicated, and ending at 1600 UT on the last day of the intervals: 20-23 Jan — latitude dependence of TIDs; 6-16 Feb (10 days whenever StratWarms first occur after 6 Feb) Stratospheric Warmings studies; 1-6 Mar Start of IPY TEC mapping; 1-3 May - Synoptic; 19-23 Jun MST/ISR, Synoptic; 11-13 Sep Synoptic; 10-21 Dec (10 days whenever StratWarms first occur after 9 Dec) Stratospheric Warmings. See http://people.ece.cornell.edu/wes/URSI_ISWG/2007WDschedule.htm. where

   Synoptic = Wide coverage of the F-region, with topside or E-region also (W. Swartz — wes@ece.cornell.edu);

   Stratospheric Warmings = Dynamics and temperature of the lower thermosphere during sudden stratospheric warming (L. Goncharenko — lpg@haystack.mit.edu);

   TEC Mapping = ISR/GPS Coordinated Observation of Electron Density Variations (Shun-Rong Zhang — shunrong@haystack.mit.edu)

   TIDs = Latitude dependence of the F-Region plasma variations during the passage of large- and medium-scale Traveling Ionospheric Disturbances (TIDs) — (T. Tsugawa — tsugawa@stelab.nagoya-u.ac.jp)

   MST = Studies of the Mesosphere, Stratosphere, and Troposphere—Coordinated D- and E-region campaigns in high resolution MST mode (G. Lehmacher — glehmac@clemson.edu);

   AO = Arecibo Obs (**http://www.naic.edu/aisr/olmon2/omframedoc.html**);

   JRO = Jicamarca Radio Obs (**http://jro.igp.gob.pe/english/radar/operation/real-time_en.php**);

   IPY = **IPY-long observations with the EISCAT Svalbard ISR** (Tony.van.Eyken@eiscat.se — https://e7.eiscat.se/groups/IPY)

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Note: an alphabetical index of names, with coordinates and page references, is given on pages 101-116.

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