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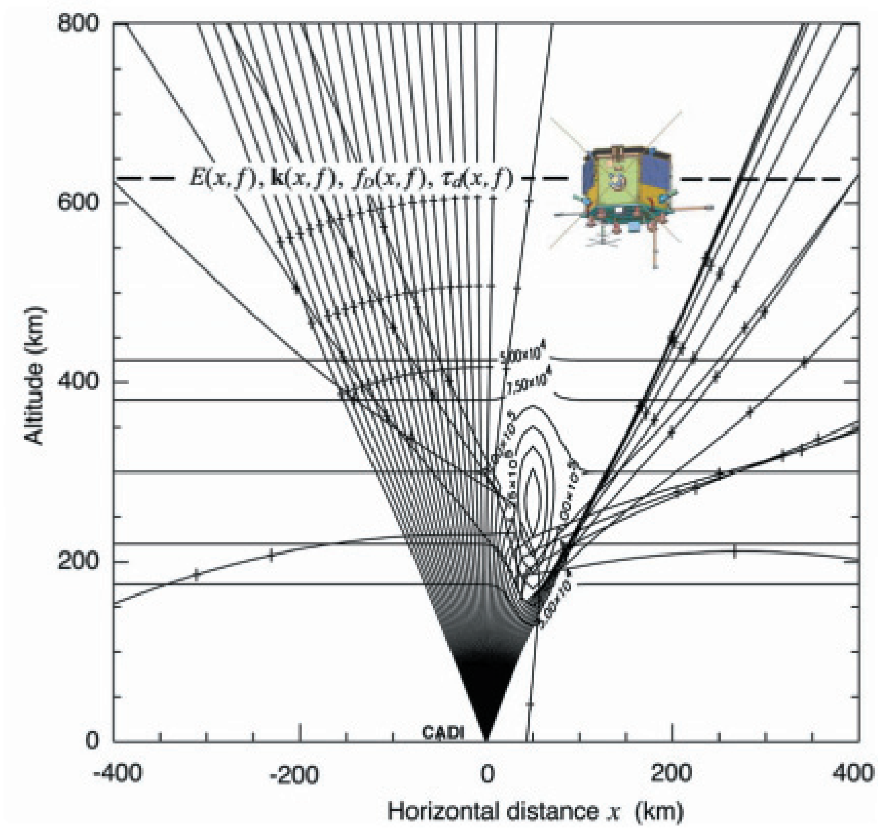

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Front cover: Rays traced from a Canadian Advanced Digital Ionosonde (CADI) are expected to show the refractive effects of ionospheric structure, such as this F-region density enhancement. In the Enhanced Polar Outflow probe (e-POP) mission, the e-POP Radio Receiver Instrument on the CASSIOPE spacecraft will measure the parameters of waves from the CADI in the topside ionosphere. See paper by H.G. James pp. 17-21.

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The International Union of Radio Science (URSI) is a foundation Union (1919) of the International Council of Scientific Unions as direct and immediate successor of the Commission Internationale de Télégraphie Sans Fil which dates from 1913.

Editorial

This is an unusually large issue of the *Radio Science Bulletin*, but that is because it is filled with lots of useful information!

Special Sections

This issue contains the second part of the "Special Sections Honoring Jenifer Haselgrove" and the Haselgrove ray-tracing equations. The first part of these special sections was in the June 2008 issue (No. 325). The Guest Editors for the special sections, Rod Barnes and Phil Wilkinson, have provided a separate Introduction for these sections. They summarize Haselgrove's career, the early development of the ray-tracing equations, the papers that appeared in the June issue, and then introduce the six papers on the subject in this issue. The efforts of the Guest Editors and the authors who have contributed such interesting papers are greatly appreciated.

World-Wide Lightning Location

Richard Dowden and 34 coauthors bring us a report on an amazing international project. They have developed a system of 30 sensors for the worldwide detection of lightning. This uses VLF propagation in the Earth-ionosphere waveguide. The paper begins with a brief description of the system and the propagation issues associated with lightning detection using VLF. The VLF antennas used in the system are then described. This is followed by a description of the method used by the system to detect and distinguish lightning strokes. An analysis of the errors in lightning location is presented, as well as a discussion of the limitations of the system. The efficiency of the system in detecting lightning is analyzed. Finally, examples of the results obtained with the system are presented, including those related to global network coverage and regional detection efficiency. A summary of the uses of the network in specific geophysical and meteorological studies is also given. This is a remarkable account of worldwide cooperation for radio science.

Two Options for Delivery of the *Radio Science Bulletin*

As announced in the last issue, the *Radio Science Bulletin* is moving to a two-tired model for delivery of the *Bulletin*, starting with the next (March 2009) issue and the new triennium. The first option (which costs 40 Euro per triennium) is for electronic delivery of the *Bulletin*. All of those choosing this option will receive an e-mail with the link to the electronic form of the latest issue when it becomes available. The second option (which costs 100 Euro per triennium) is to also receive a hard copy of the *Bulletin* by mail. All of those radio scientists who registered for the URSI General Assembly in Chicago, Illinois, in August 2008 automatically had the electronic-delivery option included in their registration by default. They were also given the opportunity to choose to add the print-delivery option, as well. If you would like to add the print-delivery option, or if you did not register for the General Assembly, you may use the form on the back cover of this issue to place your subscription. These two options more accurately reflect the actual costs incurred by URSI to prepare and deliver the *Bulletin*.

The End of One Year and the Beginning of Another

Since this is the December issue of the *Radio Science Bulletin*, it contains a wealth of information regarding radio scientists active in URSI. It also contains important information from the Chicago General Assembly, and information about those newly elected and appointed to positions within URSI. You'll certainly want to keep this issue for reference.

This issue will also reach you early in the new year. Best wishes for a most happy, healthy, safe, and prosperous New Year!

Ross

IN MEMORIAM

Femke Olyslager
1966 - 2009

Prof. Femke Olyslager passed away unexpectedly on January 28, 2009. Prof. Olyslager was born in 1966. She received the MS degree in 1989 and the PhD degree in 1993, both in Electrical Engineering from Ghent University, Ghent, Belgium. She was a full professor of Electromagnetics at Ghent University. She was a brilliant scientist who made outstanding contributions to the fields of computational and theoretical electromagnetics. She authored or coauthored approximately 300 publications in international journals and conference proceedings. She coauthored *Electromagnetic and Circuit Modeling of Multiconductor Transmission Lines* (Oxford University Press, 1993), and authored *Electromagnetic Waveguides and Transmission Lines* (Oxford University Press, 1999).

Prof. Olyslager had been the Assistant Secretary General of URSI since 2002. She was an Associate Editor of the *IEEE Transactions on Antennas and Propagation* and an Associate Editor of *Radio Science*. In 1994, she became a laureate of the Royal Academy of Sciences, Literature and Fine Arts of Belgium. She received the 1995 IEEE Microwave Prize for the best paper published in the 1993 *IEEE Transactions On Microwave Theory and Techniques*, and the 2000 Best Transactions Paper Award for the best paper published in the 1999 *IEEE Transactions on Electromagnetic Compatibility*. In 2002, she received the Issac Koga Gold Medal from URSI, "In recognition of her work on theoretical and numerical electromagnetics (in particular in the field of boundary integral equations, waveguides, and bianisotropic media)." In 2004, she became a laureate of the Royal Flemish Academy of Belgium. She was elected a Fellow of the IEEE in 2005 "for contributions to theoretical and computational electromagnetics."

Throughout her career, she showed a commitment to URSI. She will be deeply missed by the radio science community. The Department of Information Technology and its Electromagnetics group, her many PhD students to whom she was an inspiring example, and the URSI Board and Secretariat are deeply saddened by this loss of a dear friend and colleague.

Jules Aarons
1921 - 2008

Dr. Jules Aarons, a pioneer in using satellites to study the Earth's ionosphere beginning with the launch of Sputnik, died peacefully in his sleep at his home in Newton, Massachusetts, on November 21, 2008. He was 87 years old, and remained scientifically active well into his eighties. Aarons is survived by two sons and their families, his wife Jeanette having pre-deceased him.

Aarons was born in the Bronx, New York. After graduating from City College of New York in 1942, he joined the US Army Signal Corps and developed an interest in electronics. After the war, he joined the Air Force Cambridge Research Center. He also got a Master's degree in Physics from Boston University in 1949. He went to Paris on a Fulbright grant, and got his doctorate from the University of Paris under Prof. E. Vassy in 1954. This allowed Aarons to interact with European scientists early in his career. This European collaboration flourished greatly when, as an Air Force Cambridge Research Center scientist, taking advantage of the launch of the Sputnik series of satellites in 1957, he formed the Joint Satellite Studies Group (JSSG). The primary objective was to foster the collaboration of primarily NATO-country scientists in the study of atmospheric effects on satellite signals on a quasi-global basis. He had a long association with AGARD, the NATO Advisory Group on Aeronautical Research and Development, and was the Chair of its Electromagnetic Wave Propagation Panel.

Aarons' name has now become synonymous with the field of ionospheric scintillations. He showed that it is possible to make a meaningful study of plasma structuring in the ionosphere utilizing a beacon in the sky and only simple receiving systems on the ground. This allowed many developing countries to participate in this enterprise. It also necessitated the expansion of the JSSG to include many non-NATO countries in a truly global effort to understand scintillation morphology and its impact on communication systems. Thus was born the Beacon Satellite Studies (BSS) Group, with its first meeting at Graz, Austria, in 1972 under the chairmanship of Professor R. Leitinger of the University of Graz. This group remains active to this day, with biannual meetings having been held in many different venues in Europe, several in the Boston area in the US, and in Argentina, India, and China, among other countries.

Aarons published more than a hundred papers, and edited a book on *Radio Astronomical and Satellite Studies of the Atmosphere*, to elucidate the scintillation phenomena. He began his studies at middle and auroral latitudes, first using radio stars and then satellite beacons, to define an equatorward boundary for high-latitude scintillations. He showed that the VHF scintillation boundary was more equatorward of the low-energy particle-precipitation boundary, and that its dynamics were controlled by magnetic activity. From that vantage point, he extended his studies both to polar and equatorial latitudes. He was the first to point out that there were large scintillations in the polar-cap ionosphere, especially during years of maximum solar activity. He was also the first to point out that low-latitude scintillations did not maximize at the magnetic equator, but at the crests of the equatorial anomaly in F-region ionization. He encouraged and supported the construction of many ionospheric-monitoring stations, in collaboration with numerous colleagues from around the world.

With the advent of geostationary satellites, Aarons immediately recognized the value of time-continuous total electron content (TEC) and scintillation measurements at these various locations. His foresight and vision in setting up these stations greatly improved our worldwide understanding of scintillation morphology and TEC variability. In particular, his research on equatorial scintillations, combined with radar and satellite in-situ measurements, provided much insight into the physics of plasma structuring, an endeavor in which Santimay Basu and myself were active partners. It is quite instructive to recognize that because of the far-flung stations he established, his laboratory could help the Air Force in its planning for space-based communication and navigation systems. For instance, J. A. Klobuchar, working with Aarons, developed an algorithm to reduce by approximately 50% the ionospheric-range-delay errors in single-frequency Global Positioning System (GPS) receivers for navigation. This model is still in use by the GPS system, twenty-five years after its development. This group's research on ionospheric physics and its system applications thus laid the foundation for what is known today as ionospheric space-weather studies. In the larger context of the sun-Earth system, space-weather research, with its societal benefits, has now become a topic of great interest to the global community of space scientists, and the civilian and defense agencies that support their work.

Given his international outlook, Aarons was able to attract and mentor scientists from all over the world, who were eager to benefit from the global archive of scintillations and TEC data he had so assiduously built. His laboratory played host to a galaxy of foreign associates, and, of course, several from within the US, as well. These people generally visited for extended periods of time as US National Academy/ National Research Council scholars. In addition to many European scientists, he welcomed colleagues from as far away as India, Australia, and Israel, to name a few places. His long-term guidance and mentoring of these colleagues and their mutual interactions have transformed the BSS Group into a close-knit international community.

During his tenure of more than thirty years as an Air Force scientist, Aarons was recognized with the Exceptional Civil Service Award and the Gunther Loeser award for scientific achievement. His *alma mater*, the City College of New York, honored him with the Townsend Harris Medal. Aarons was very active in professional organizations, such as the Institute of Electrical and Electronics Engineers (IEEE) and the International Union of Radio Science (URSI). He was elected a Fellow of the IEEE, and honored with its Harry Diamond Memorial Award. He served both the US National Committee of URSI and international URSI as the Chair of Commission G on Ionospheric Radio and Propagation (he was Chair of international Commission G from 1980-1983).

After his formal retirement in 1981 from the Air Force Geophysics Laboratory, as it was then known, he joined Boston University as a Research Professor in the Department of Astronomy, with close ties to the Center for Space Physics. His wise counsel was much appreciated by faculty and graduate students alike. At Boston University, working closely with Michael Mendillo, he launched scintillation studies using a worldwide network of stations monitoring the GPS satellites. His major interest was to elucidate the effects of magnetic storms on the equatorial and high-latitude ionosphere by the use of transmissions from these satellites and other supporting measurements. This phase of his career, which continued into the ninth decade of his life, was very fruitful, producing more than 30 journal publications. During this post-retirement period, the prestigious Appleton Lecturer award of the Institution of Electrical Engineers (IEE) was bestowed on him in 1996. After Aarons turned 80, several special sessions were held in his honor. One was held at the BSS Group Meeting at Boston College in July 2001, with the proceedings of the symposium featuring a warm tribute to him written by his long-time associate J. A. Klobuchar. Another special session was held at the European Geophysical Society (now EGU) and the American Geophysical Union Joint Meeting in Nice, France, in 1983, which resulted in a guest editorial in *Annales Geophysicae* by this author in 2004. Aarons' insatiable thirst for knowledge, his personal warmth and genuine concern for colleagues from around the world remained the hallmarks of his long career until the very end of his life.

Aarons was one of those rare individuals who was not only recognized as a distinguished physicist, but was also highly acclaimed as a talented photographer. He always felt a creative impulse that science alone could not satisfy. However, his scientific pursuits allowed him to travel widely, so that this self-taught photographer could indulge in his passion for street photography, not only in the ethnic neighborhoods of Boston, which have long vanished, but also in Europe, South America, and Asia. He has photographs in the collections of the Museum of Modern Art (New York), Bibliotheque Nationale (Paris), and the Museum of Fine Arts (Boston). He has had one-person photographic shows at galleries in the Boston area, New York, and Paris. In 2003, a retrospective of his photographs over thirty years was exhibited at the DeCordova Museum in Lincoln, Massachusetts. In the introduction to his book *Street Portraits, 1947-1976: The Photographs of Jules Aarons*, the Curator of the DeCordova Museum, Rachel R. Lafo, wrote,

> Aarons' interest in and empathy with his subjects enabled him to capture quotidian moments that resonate with a *joie de vivre,* whether the subject is a street performer in Paris or a girl running down the sidewalk in Boston. Even though he was not trained as an artist, Aarons quickly mastered the technical aspects of photography, producing images with dramatic shadows and highlights, formally structured compositions, and timeless presence."

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[Author's note: This article was adapted from "Jules Aarons – Space Scientist and Mentor," guest editorial in honor of Dr. Jules Aarons, by Sunanda Basu, published in *Annales Geophysicae*, **22**, 2004, pp. 3087-3088, and material from there is used with permission. The photo of Jules Aarons accompanying this article is by Santimay Basu.]

Introduction to Special Sections Honoring Jenifer Haselgrove

Even a significant historical achievement may diminish in its apparent magnitude if too casually viewed through the prism of our present state. This is vividly portrayed in the world of computing, where an information age now looks back on enormous machines, with their clumsy human interfaces and relatively small processing and memory capabilities. Of course, more careful scrutiny reveals that what was achieved with those relatively primitive computers was far from trivial. After all, the birth of computers was concurrent with the second World War, and success and failure could be seen in very stark terms. The first automated computers emerged in Germany, the US, and the UK in the 1940s. EDSAC, the first UK general-purpose stored-program computer, was commissioned at Cambridge in 1949.

In 1950s' Cambridge, the scene was set for a young PhD student named Jenifer Haselgrove (Figure 1) to make a remarkable connection, which would end up greatly benefiting the world's radio-science community.

Figure 1. Jenifer Haselgrove

According to Haselgrove, "these were heady days, where everything you did on a computer was new." An abstract from her recent musings on those times provides insight, and it is curious to get a glimpse of the early utilization of computer-science constructs that have stood the test of time, such as functions and libraries:

> The programming language was a simple mnemonic code, for example, "A 150" meant "add the number in storage location 150 into the accumulator [the place where the current working number was]." You didn't have to think in binary arithmetic, contrary to what you read in some historical accounts of early computers nowadays. The program (that spelling was settled on for use even in Britain fairly early, after some argument) was typed on to 5-hole (teleprinter) paper tape and read into the machine by a single built-in program of "initial orders." The instructions making up programs were called orders, which may have been a bit confusing at first, but nothing like the terrible mistake made in FORTRAN and later languages, where instructions are called "statements." Of course, programs didn't all do numerical work – take the initial orders for example – and there had to be programs right from the beginning to read users' programs and data and to print results. Those were part of a whole "library" of subroutines for standard jobs, including numerical ones such as calculating square roots, and even division, which wasn't originally built in. At first the output was directly on to a teleprinter, typing on paper at, I think, 7 characters a second, but later that was changed to punched tape like the input, to be printed later or while the machine got on with the calculating. The actual computing building was the original Anatomy Department, and there was a coffin lift (elevator) in one corner. I don't think any of us bothered about that, though, even working alone in the building in the middle of the night. We all had to do some of that – machine time was rare and valuable!

Jenifer Haselgrove had begun her tertiary education after moving to Cambridge (Figure 2) in 1948, where she started reading math. At that time, she connected with Brian Haselgrove when they both joined a music group, which listened to "long-playing records," a recording and playback technology that intrigued them both. They married in 1951. In the same year, she moved to physics and the Cavendish Laboratory. When meeting the seniors on the board of the Cavendish Laboratory, Haselgrove was a little taken back to find them expressing relief that she was not interested in practical or field work. Curious on whether she was running up against some Cavendish misogyny, she was amused to hear later, after some discrete inquiry with the departmental secretary, that the panel was greatly concerned about the lack of "facilities" at the field station! Furthermore, the secretary had chided the board for being silly, suggesting "they could use one bush and Haselgrove another."

Figure 2. Richard Haselgrove, Jenifer Haselgrove's brother, supplied this photograph from earlier Cambridge days. Jenifer is fourth from right, front row. Brian Haselgrove (her first husband) is fifth from right, front row. John Leech (her second husband) is fifth from left, back row.

Haselgrove was just starting her research when she fell pregnant, and 1952/3 was spent preparing for and rearing her son. Her early postgraduate research was performed under the renowned radio scientist Kenneth Budden, where she started on radio propagation, spending time calculating the trajectory of short ray paths by hand. Many other researchers were similarly developing mathematical and analytic techniques and constructs to further the domain of radio ray tracing through that time. Shortly afterwards, in discussions with her husband – himself a highly respected mathematician who was now working with EDSAC in the math department – she was encouraged to look at ways to solve the ray-propagation problem on a computer. Her first work on the topic was published shortly afterwards, and over the next five years a series of papers were published (all referenced in the articles to follow). Subsequent to her breakthroughs, there is record of numerous efforts in computer-based ray tracing emerging throughout the world. Jenifer Haselgrove had developed the connection that resulted in the birth of her second creation, computer-based radio ray tracing. By the early 1960s, the radio-science community was on board and was enamored with her latest "child." Through popular use, her name is now enshrined with the original formulations, viz., the *Haselgrove Equations*. The equations derive from the physical-principle formulations of William Rowan Hamilton and James Clerk Maxwell, when applied to radio propagation in the ionosphere. Haselgrove herself referred to them as Hamilton's ray equations.

Haselgrove worked on ray-tracing problems in collaboration with her husband, until he died in 1964. After that, she remarried to John Leech, another Cambridge mathematician who had worked and socialized with the Haselgroves through their careers. Jenifer Haselgrove worked as a computer scientist at Glasgow University, and retired in 1981.

A two-part collection of articles in the June and December editions of the *Radio Science Bulletin* has been developed. It amounts to a dedicated effort by a group of radio scientists who have benefited from the path pioneered by Jenifer Haselgrove, and have taken the time to honor that achievement.

Of note is the variety of applications to which the Haselgrove Equations and computer-based ray tracing have been applied. Topics include EHF, VLF, and HF electromagnetic propagation in the magnetosphere; whistlers; HF communications; inter-satellite communications; HF radar; HF radio direction finding; and remote-sensing investigations of the ionosphere and magnetosphere. Many of these topics are touched on with the following papers. The same equations also provide solutions for acoustic ray tracing.

Part 1 of the testimonial editions appeared in the June 2008 issue (No. 325). It started with a theoretical treatise by Coleman, who demonstrated a method of deriving the Haselgrove Equations directly from Maxwell's equations. In the next article in the series, Nickich discussed his career and the foundational role that radio ray tracing, based on the Haselgrove Equations, played in this. Finally, Barnes discussed two applications of ray tracing at HF, pertaining to sounders and radar.

The June issue also contained the Commission H contribution by Walker, which summarized the changes needed when following the propagation of longer-period (10 to 40 seconds and greater) magnetohydrodynamic waves in the magnetosphere.

The second part of the testimonial appears in this issue. It begins with a historical summary of ray-tracing development by Bennett. Dyson then discusses the impact of the Haselgrove Equations and ray tracing on his career in radio science. This is followed with a summary of high-frequency radio wave applications developed by Bertel.

James provides a summary of multiple applications of the Haselgrove Equations. Kimaru discusses a career that began almost simultaneously with Haselgrove's, which involved the application of her ray-tracing techniques to whistler and other wave propagation in the magnetosphere. Finally, Walker reviews the application of Haselgrove's method in the magnetosphere, providing physical insights and some current and historical applications of the method.

Please enjoy the final part of this tribute to Jenifer Haselgrove and her achievements. In collating and researching for this work, we have been inspired by many of the great minds that have brought us so far in radio science, but none more than Jenifer Haselgrove and those around her at Cambridge, which led to her famous formulation and her use of one of mankind's first computers to solve it. Our hope is that these editions draw your attention to those "heady days," a person who lived through them, and her achievements. Just as importantly, it is hoped that it inspires you in your radio-science endeavors so that someone may write about them with great respect in the near future.

Rod Barnes and Phil Wilkinson
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Correction

An editing error was made in the paper by P. J. Hall, R. T. Schillizzi, P. E. F. Dewdney, and T. J. W. Lazio, "The Square Kilometre Array (SKA) Radio Telescope: Progress and Technical Directions," *Radio Science Bulletin*, No. 326, September 2008, pp. 4-19. "Square Kilometre Array" is in fact a proper noun (it is the internationally agreed-to logo and name for the telescope), and the spelling of "Kilometre" should not have been changed to match the style used for the corresponding unit in the *Radio Science Bulletin*. The *Bulletin* regrets the error.

Some Reflections on the Tracing of Radio Rays in the Ionosphere

J.A. Bennett

Abstract

This short contribution outlines some developments in ionospheric radio ray tracing in which I have been involved. Many of these developments, though theoretical in nature, were directed toward making numerical ray tracing more effective and more powerful. I am grateful to be able to make this contribution in honor of Jenifer Haselgrove (now Leech), and her contribution to the tracing of radio rays in the ionosphere.

1. Introduction

When I started my research, Dr. J. A. Thomas gave me the task of building equipment to measure the small Doppler shifts experienced by ionospherically propagated radio waves due to time changes in the ionosphere, particularly those associated with solar flares. I was surprised to find that there did not appear to be a known general formula for calculating the Doppler shift from the changes in the ionosphere. This got me thinking deeply about the rays, and particularly derivatives or variations of various quantities associated with the rays. I have remained interested in the topic for over 40 years. I never did build that equipment.

About this time, my future wife gave me a copy of Budden's monograph [1] for my birthday. I read and re-read it while commuting to and from the university by train. This book was mostly concerned with plain stratified media. It showed how useful the ray approach can be in this case. However, as this geometry admits solutions of Maxwell's equations by separation of variables, it is not a natural place to start in developing a ray description of propagation in a general inhomogeneous medium, such as the ionosphere. Budden also referred to the work of Haselgrove [2, 3], and discussed a number of applications of ray tracing in general media. This seemed a good place to start. I then turned to the original work of Hamilton [4], as had Haselgrove. There I found almost everything I needed.

2. Doppler Shift

It was recognized that using the idea of an instantaneous frequency, which was a reasonable approach in the circumstances, the Doppler shift experienced by a radio wave was given by

$$\Delta\omega = -\frac{\omega}{c}\frac{dP}{dt}, \tag{1}$$

where P, known in the ionospheric world as the phase path, can be written as

$$P = \int_A^B \mu \cos\alpha \, ds \cdot \tag{2}$$

The integral is taken along the ray from point A to point B (for the present regarded as fixed), μ is the refractive index, α is the angle between the ray direction and the direction of phase propagation, and s is arc length. The question is, how to carry out the differentiation under the integral sign? If the properties of the ionosphere vary with time, then the refractive index varies with time, as does the ray path.

3. Hamiltonian Formulation

Hamilton [4] developed a geometrical formulation of optics that involved families of rays. He showed that the rays could be defined as the solutions of a variational problem. This result is known as *Hamilton's Principle*. We express it here as

$$\delta\int_A^B \mathbf{p} \bullet d\mathbf{q} = 0 \tag{3a}$$

subject to

$$H(\mathbf{p},\mathbf{q}) = 0, \tag{3b}$$

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where δ is an operator that represents the first-order change or *varia*tion between the true ray and competing curves (strictly strips) that are not themselves rays. For the moment, regard the endpoints as fixed. $\mathbf{p}$ is a vector lying in the direction of phase propagation, with length equal to the refractive index, μ. Equation (3) thus represents the possible values of $\mathbf{p}$ that can exist at a point $\mathbf{q}$. It can be written in many forms. It can be shown that the solution of Equation (3), with fixed endpoints, satisfies quasi-linear first-order ordinary differential equations that can be written as

$$\mathbf{q}' = \theta \frac{\partial H}{\partial \mathbf{p}}, \tag{4}$$

$$-\mathbf{p}' = \theta \frac{\partial H}{\partial \mathbf{q}}.$$

These are the Hamiltonian form of the ray equations, here written in Cartesian coordinates. In the ionospheric literature, particularly when expressed in spherical coordinates, they are widely known as Haselgrove's equations. Haselgrove always referred to them as Hamilton's ray equations. The value of the scaling function, θ, depends upon the form in which $H(\mathbf{p},\mathbf{q})$ is written, and the choice of the parameter μ. Not all choices are equally convenient for numerical work. Haselgrove considered this issue.

It is sometimes useful to consider variations between true rays: for example, rays existing at different times, at different frequencies, with different endpoints, etc. It is convenient to distinguish these variations from those described in association with Equation (3). We thus consider a variation represented by $\delta_m \bullet = (d \bullet / dm)\delta m$. Hamilton considered such variations, and in at least one instance, used the subscript notation. Unfortunately, some have had difficulty distinguishing between δ_m and δm. It is most convenient to carry out the calculations using the Hamiltonian formulation. We include the possibility that H depends explicitly on m.

The corresponding variation of P is given by [5]

$$\delta_m P = \int_A^B -\theta(\partial H/\partial m)\delta m\, du + [\mathbf{p} \bullet \delta_m \mathbf{q}]_A^B, \tag{5}$$

where, by definition, the derivative of H with respect to m is taken at a fixed point and in a fixed wave-normal direction.

It is possible to consider higher-order variations [5]. For example, introducing an independent variation represented by $\delta_n \bullet = (d \bullet / dn)\delta n$, we can find $\delta_m \delta_n P$. Various forms of the result are possible. We omit details, and point out an important property of the resulting expressions. In contrast to the first variation, the second variation of the phase path does depend upon variations of the ray path. It can be written in forms that involve only one of the m or n variations of the path. These variations may be determined by solving the equations that arise when we vary the ray equations. In order to obtain sets of equations capable of being solved, it is necessary in some way to specify which points on the rays are being compared.

4. Doppler Shift Again

In Equation (5), identify m with time. In this case we do not really need the variational notation. Choosing u as arc length and carrying out the differentiation, from Equation (1) we obtain

$$\Delta\omega = -\frac{\omega}{c}\left\{\int_A^B \frac{\partial \mu}{\partial t}\cos\alpha\, ds + \mathbf{p}_B \bullet \mathbf{v}_B - \mathbf{p}_A \bullet \mathbf{v}_A\right\} \tag{6}$$

If the end points of the ray are thus stationary, the Doppler shift depends upon the derivative of the refractive index taken along the ray. The path of the ray changes, but it makes no contribution to the derivative of the phase path. When my first paper giving this result [6] was about to appear, I learned that Jones [7] had included this result in his ray-tracing program. I was assured that he had not actually derived the result, and I did not need to withdraw my paper. Presumably, he included the equation because it was obvious to him. However, the result appeared counter-intuitive to a number of workers, and took a little time to be generally accepted. This derivation also gives the Doppler shift that results when the end points, *A* and *B*, move at low velocities, $\mathbf{v}_A$ and $\mathbf{v}_B$, respectively. Again, changes in the ray path make no contribution to the Doppler shift: only the end-point terms contribute. Using a space-time form of Hamilton's principle, the result of Equation (6) can be generalized to apply to more-rapid changes [8].

5. Further Applications of Ray Variations

There are other applications of ray variations besides the calculation of Doppler shifts. These include the systematic development of approximate solutions, applying at frequencies where the rays are almost straight, and calculating ray tubes for homing-in and power calculation. Another application is calculating the effect of small changes in the ionosphere on such quantities as phase path, group path, and angle of arrival. All of these calculations may be carried out numerically at the same time as tracing the principal ray [5, 9]. A number of these applications have been discussed in a recent review [10], and that discussion will not be repeated here.

6. Geometrical Optics and Quasi-Optics

Rather than the purely geometrical approach, rays can be understood as arising in the construction of an approximate solution of Maxwell's equations using the idea of frequency scaling. The results of Lewis [11, 12] are sufficiently general to apply to the ionospheric case, but were not well know to the ionospheric community. I have made a contribution to publicizing the approach, e.g., [13]. In this approach, the rays arise as characteristic curves used in solving the partial differential equation often known as the equation of the eikonal. In the notation used here, that equation is

$$H\left(\partial P/\partial q, \mathbf{q}\right) = 0 \cdot \tag{7}$$

A number of results that are not obvious from the geometrical approach are obvious from the approach via the equation of the eikonal, and visa-versa. For example, from the derivation leading to Equation (5), we see that $\mathbf{p}$ represents the gradient of P. As characteristic curves, the rays are determined precisely so that this will be the case. The two approaches are connected by the *Hamilton-Jacobi* partial differential equation from the calculus of variations. This is the same equation as given by Equation (7). We gain more information from the approach via Maxwell's equations. There is an additional phase shift associated with the vector nature of the waves [12, 14, 15]. Hamilton's theory tells us nothing about this.

Carrying through the development of the approximate solutions in the case of a strongly absorbing medium leads to complex rays [13].

7. Closed-Form Ray Tracing

Despite the tremendous improvement in the power and speed and the falling cost of digital computers, there are occasions when simplified, more-rapid ray tracing is desirable. If the ionosphere is assumed to be spherically symmetric and the radial ionospheric structure is represented by suitable functions, the ray equations, including those describing varied rays, can be integrated to give closed-form results [16, 17]. An approximate inclusion of magnetoionic effects is possible [18].

8. Conclusions

In adopting the Hamiltonian form of the ray equations, Jenifer Haselgove made a huge advance in the study of ionospheric radio propagation. She showed herself to be well ahead of her time. This paper covers a number of developments in ray tracing in which I have been involved. It does not adequately cover my collaboration with Peter Dyson, which he has commented on elsewhere in this volume. Such advances do not arise out of nothing, but follow advances made by others. Also, as frequently happens in science, some results were discovered and rediscovered. In a contribution of this form, it is not possible to include a comprehensive list of references. I apologize to readers who may feel I have neglected their work. I have included some anecdotal material, in the hope that it will show what an exciting field developed from Haselgrove's pioneering work. Some results that were controversial and stimulated animated discussion at the time we now accept as commonplace.

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A Tribute to Jenifer Haselgrove

Peter L. Dyson

In 1964, I began my PhD at the University of Melbourne in Australia. My research project was to study the topside ionosphere, a region which had only recently become possible to explore in detail using the topside-sounder satellites, Alouette (Canadian) and Explorer XX (US). I used a hand-directed crossed-Yagi antenna to track these satellites and obtain observations of the topside ionosphere over the Australian region. I quickly realized that to explain the modes of propagation giving rise to the assortment of echoes observed on topside ionograms would require a general ray-tracing technique that included the full magneto-ionic effects, and that allowed arbitrary electron-density structures to be specified. My search of existing techniques quickly brought me to Haselgrove's equations, which provided a completely general ray-tracing technique that could be readily translated into computer code. So, I wrote such a computer program, and produced the first [1] of many studies that utilized ray tracing using Haselgrove's equations.

After my PhD, I spent two years at NASA Goddard Space Flight Center, where my interest was primarily in studying the nature of ionospheric-irregularity regions using satellite-borne direct-measurement probes. In 1969, I returned to Australia, taking up a position at La Trobe University. I turned my attention back to using radio techniques to study the ionosphere, as well as airglow techniques to study the thermosphere at F-region heights.

John Bennett and I were PhD students together and after spending some time in Canada, John also returned to Australia, to Monash University, which, like La Trobe, is located in suburban Melbourne. John's research developing the theory of radio-wave propagation and applying the results to ionospheric situations was of interest to me. He invited me to collaborate on applications of ray theory to ionospheric problems. While our papers did not always use ray tracing per se, we presented results in the form of equations that we knew could be added to Haselgrove's equations to calculate additional properties of radio waves, such as absorption [1], Doppler shift [2], and the effect of certain types of ionospheric irregularity [3].

John developed equations to determine the spreading of a ray tube along a ray path. These provided an efficient means of homing-in to specified targets or locations. This led us to develop our own ray-tracing package, which we named *HIRT* (Homing-In Ray Tracing). *HIRT* was widely used by us and some of our collaborators from the late 1970s. However, the homing-in feature initially applied only to an isotropic ionosphere. It was not until much later, when Robert Norman applied John Bennett's general formalism to derive the homing-in equations for an anisotropic ionosphere, that *HIRT* was written up in any form [4].

From the time I wrote my first ray-tracing program based on Haselgrove's equations, I was a strong advocate for their use in ionospheric applications. Through contracts with the Australian Defence Science and Technology Organisation, related to the development of the Jindalee over-the-horizon radar (OTHR), John Bennett and I began to apply numerical ray tracing to problems in OTHR in ~1985. However, we soon realized that at that time, the computational overhead of numerical ray tracing made it inappropriate for most real-time applications. This led us to also develop techniques to extend the situations to which analytical ray tracing could be applied, to give acceptable real-time results in operational systems (e.g., [6]). Of course, we continued research using numerical ray tracing (e.g., [7]), since analytical ray tracing will always be of more limited use.

As indicated above, Jenifer Haselgrove's development of a set of equations describing the application of Hamiltonian principles to radio-wave propagation in a completely general ionosphere opened up a whole area of research for me from the very beginning of my career as a PhD student. Of course, I am only one of many for whom this is true. I think it is accurate to say that her equations have been the foundation on which much of the research on the interpretation of HF propagation via the ionosphere has been built.

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Applications of the Haselgrove Equations

Louis Bertel

Around 1970, a ray-tracing facility at Rennes University, based on the Haselgrove Equations, was implemented in a series of stages. The form of the equations used was based on those given in Kelso [6], with modifications as required to implement the various stages. Each stage addressed a greater degree of complexity required to solve the different propagation objectives.

1. Trans-Ionospheric Propagation

The first stage ignored the magnetic field, and modeled the ionosphere as a single parabolic layer (1966-1970). The main objective was to determine mathematical models for the Doppler effect [2], and then the wave-trajectory and refraction effects. The principal student associated with this work was Guy Joliff, whose thesis was completed in 1969. The work was carried out in 1967-69 on a small computer, the first computer at the University of Rennes. Solutions were sought over a range of frequencies, with computations being limited to a small selection of frequencies ranging from 20 to 360 MHz (20, 40, 41, and 360 MHz). While the main objective of this study was to determine the wave trajectories and, hence, the phase and group delay paths, the length of the trajectory was also determined. A homing process was used in the first software implementation, but it took too long. Consequently, new initial conditions, based on Bouguer's law, were developed, leading to the solution of the integral equations. The results were published by Bertel et al. in 1971 [3]. Subsequently, the integral solution was used for frequencies above about 100 MHz, taking into account the accuracy of the mathematical method and the computer possibilities (32 bits and double precision). The principal student associated with this work was Miss Claude Castrec, whose thesis was completed in 1970. The main applications were for ray tracing to satellites (e.g., the BE B and BE C satellites, and the Transit satellites). A range of frequencies from 20 MHz up to 400 MHz was used, and the results were published by Bertel in 1969 and 1971 [2, 3].

The second stage was carried out during 1970-1972. The parabolic profile was limited for some applications, so a more realistic profile was constructed to represent the ionosphere. The single-parabolic-layer ionosphere was replaced with a Chapman layer, with two scale heights: a 50 km scale height for the lower part of the layer, beneath the layer peak, and 73 km for the upper part. The effect of the magnetic field was introduced in a simplified way, using a frequency shift. The main objective of this stage was to study the ionospheric Doppler effect. By using the Chapman profile in this step, it was also possible to introduce atmospheric gravity-wave effects. The initial conditions for solving the equations were set using the method described in Bertel and Geslin [4]. Solutions were sought over a range of frequencies, with computations being limited to a small selection of frequencies ranging from 20 MHz to 150 MHz and 400 MHz.

The next step, carried out between 1970-1975, used a more complex ionospheric model and included the magnetic field, an anisotropic medium. The main objective was to study the Faraday effect, and the relationship between the Faraday and Doppler effects. The ionosphere was represented by a Chapman layer, similar to the previous stage, having a scale height of 50 km below the layer peak and 73 km above. The layer was described by a fifth-order polynomial. The magnetic field was taken into account. Solutions were restricted to frequencies in the range of 20, 40, and 41 MHz, and applied to Satellites BE B and BE C. The principal student associated with this work was Daniel Geslin, whose thesis was completed in 1971. In order to solve the equations, numerous hypotheses were introduced, and some terms were neglected (e.g., the derivatives of the components of the electromagnetic field). Simultaneous ionospheric Doppler-shift measurements with Faraday rotation were made from the BE B and BE C satellites, and the experimental and theoretical results obtained in different cases were compared. For mid-latitudes, the results were practically the same. Thus, a simple method of simulation was sufficient. The principal results were published by Bertel in 1971 [3] and 1972 [4].

2. Ground-to-Ground Propagation

The next stage was to apply the method to point-to-point radio circuits. Further techniques were developed using a multi-quasi-parabolic profile, with a homing process [5]. However, in this solution the Haselgrove equations were not used (e.g., [1]).

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In all of the applications, the radio wave was always assumed to propagate in the same plane (i.e., in the plane defined by the satellite, the observing station, and the center of the Earth). Transverse ionization gradients were not taken into account.

The mathematical solution for the Haselgrove equations can be summarized as follows. The initial conditions for solving the equations were given by Bertel et al. [3]. From Bouguer's or Snell's law, it is possible to determine the initial conditions (the angle of elevation or departure of the wave), as well as the phase path and the group path from geometrical considerations. In the case of propagation in an isotropic medium, the two methods (Haselgrove and the integral equation) are practically identical, and the methods have been used successfully up to 10 GHz. The numerical methods for solving the Haselgrove equations, also given by Bertel et al. [3], were developed with the help of the University of Rennes mathematical group (particularly, Jean Le Faou). The Runge-Kutta method was originally applied, and subsequently other methods have been used on many different computers.

Finally, there have been many applications of these ray-tracing programs, a few of which are shown in Table 1.

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Application	Technique	Authors
Determination of the order (in frequency) of the different terms in Doppler and Faraday effects	Initial method Haselgrove, if the frequency is below 100 MHz [3]	Bertel [1] Bertel et al. [3] Bertel and Geslin [4]
Transionospheric propagation: determination of the phase delay (and Doppler shift), group delay, and angle of arrival (isotropic case); Determination of the effects of atmospheric gravity waves	Haselgrove, if the frequency is below 100 MHz, determination of the refraction. Integral equation for all frequencies and determination of the limits of application of simple formulation, case of frequencies greater than 100 MHz (Bertel and Geslin [4])	Bertel et al. [3], Lassudrie et al. [7] Sizun et al. [8]
Ground-to-ground propagation, radio direction finding, and HF radar	Integral equation using a multi quasi-parabolic profile. (Bertel and Geslin [4], Brousseau and Bertel [5])	Bertel and Geslin [4], Brousseau and Bertel [5], Baltazart [1]

Table 1. A few applications of ray-tracing methods.

Understanding Solar-Terrestrial Plasmas at a Distance with the Haselgrove Equations

H.G. James

1. Introduction

The study of radio sources at a distance is an important aspect of ionospheric radio science, contributing to understanding of the ionosphere-magnetosphere system. Geospace plasmas have presented a number of challenges. One is that in the interpretation of received electromagnetic (EM) waves, the researcher generally contends with the combined effects of the source characteristics, propagation, and the physics of receiving antennas. Another particular challenge arises in electrostatic (ES) plasma waves. They are important because of their involvement in the interchange of energy in important localized regions of the ionosphere-magnetosphere. However, these electrostatic waves sometimes need to couple or convert to long-wavelength cold-plasma electromagnetic (EM) waves to indicate their existence, whether the receivers are on the ground or in space [1]. Jenifer Haselgrove's equations [2, 3] made a timely appearance at the beginning of the space-science era. The Haselgrove equations (HE) helped to meet the above challenges by supplying a tool for the analysis of electromagnetic propagation in the ionosphere-magnetosphere. Her Hamiltonian formulation had the generality needed to account for the sometimes complicated three-dimensional structure of geospace magnetoplasma. Subject to the scale-size limitations of geometric or ray optics expressed in the Wentzel-Kramers-Brillouin (WKB) criterion [3], the Haselgrove equations have been developed for different wave-dispersion relations and then applied to a variety of research.

This note outlines the author's experience in applying the Haselgrove technique to the investigation of a variety of processes of distant waves, of either spontaneous or artificial origin. Related work by other authors is added to provide context. This paper lists work in which the Haselgrove equations have been used a) to study the direction of propagation and the intensities of waves from solar and auroral-ionosphere spontaneous sources, b) to interpret the behavior in the ionosphere of radio waves from transmitters in space and on the ground, and c) with data from active space-radio experiments, specifically to increase our appreciation of all three spatial dimensions in the injection, propagation, and detection of waves. Reference herein is also made to wave-propagation investigations by the author that apply simplified versions of the Haselgrove equations, permitting a better appreciation of the wise use of the Haselgrove equations as a research tool.

It is clear from other papers on the Haselgrove equations in this issue of the *Radio Science Bulletin* and their bibliographies [4-6] that a major motivation for the development of ray tracing has been improved understanding of the physics of high-frequency (HF) radio waves emitted or received by ground-based communications and radar facilities. The objective of this note is to outline the author's career path through a variety of space-radio-science subjects, mostly not in terrestrial HF. These include observations of both spontaneous wave sources in the ionosphere-magnetosphere and artificial emitters, in a basic-science context.

2. Spontaneous Waves in the Whistler Mode

A prime example of a spontaneous radio phenomenon bringing us information about the distant magnetosphere is the radio emission called the whistler [7]. Whistlers result from lightning strokes in the lower atmosphere, and have been of sustained interest from before the beginning of the space age. Quantitative analyses of whistlers were first applied to the probing and exploration of the plasmasphere [8, 9]. More recently, interests in whistler-mode emissions have widened because of their role in magnetosphere-ionosphere-neutral-atmosphere coupling [10-12].

Whistlers propagate in the "whistler mode," the right-hand circularly polarized EM mode of propagation predicted by the cold-plasma dispersion relations for frequencies above the lower hybrid resonance, and below the lesser of the electron plasma frequency and the electron

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gyrofrequency [3, 12]. This mode is of great interest in the ionosphere/magnetosphere, because waves in the EM whistler mode, or its electrostatic extension, participate in a variety of wave-particle interactions.

How lightning EM radiation couples into the equatorial magnetosphere through either irregularity-guided or unguided propagation was of the early interest. The Haselgrove equations in spherical coordinates [13] have been applied to demonstrating the role of ionospheric F-region horizontal gradients in affecting the propagation directions of rising whistler-mode radiation at low and middle latitudes [14, 15]. These applications exploited the versatility that the Haselgrove equations offered in conjunction with three-dimensional models of the ionosphere.

3. Methods Applied to In-Situ Studies of Radio-Wave Propagation in the Ionosphere

The Haselgrove equations have been applied to explaining features of EM propagation modes in the ionosphere. As illustrated in Figure 1, the Haselgrove equations have been used to show how a pervasive downward gradient of electron density in the topside ionosphere confines medium-frequency (MF) O- and X-mode rays from an isotropic EM source to an upward-opening caustic envelope [16], thereby endowing the source with upward directional gain. Considerations of focusing can also be important for receivers, for the interpretation of spaceborne observations of extraterrestrial MF and HF sources [17, 18]. The Haselgrove equations can be applied to the prediction of the evolution of Poynting flux in a bundle of rays [2] from any radiator through a smoothly inhomogeneous medium to a receiving site. There, the variation of field strength with direction allows the calculation of radiated energy from an emitting source. This technique is useful in examining the properties of spontaneous auroral MF sources in the O mode [19] and in the X mode [20]. The same technique has been applied to the whistler-mode measurements of the ELF-VLF modulated auroral electrojet [21, 22], and spontaneous VLF sources at high latitude [23].

Systematic dispersion of pulsed signals during ionospheric propagation, to be expected from the combination of the magnetoionic theory and the Haselgrove equations, has sometimes been masked by effects outside the realm of ray optics. Spectacular pulse stretching indicated scattering of MF waves propagating near the lower- or upper-oblique resonance cones [24, 25]. In the investigation of HF backscatter observed at close range in the topside ionosphere, the Haselgrove equations were employed together with models of the ionospheric density to quantify refractive effects. This permitted conclusions about values of the cross sections for coherent backscatter, which backscatter is mostly observed at comparatively long range by ground radars [26].

As mentioned in the introduction to the first special section [27], the Haselgrove equations have been used theoretically to evaluate propagation links between locations in the ionosphere or on the ground. The objectives of research with the Haselgrove equations have sometimes gone beyond determining the existence of connecting rays. Signal phase, $\phi = \int \mathbf{k} \bullet d\mathbf{r}$, integrated along the Haselgrove equations' ray path for frequency components of a particular emitted spectrum – say, a pulse spectrum – can be used to compute the total complex spectrum at the ray end point,

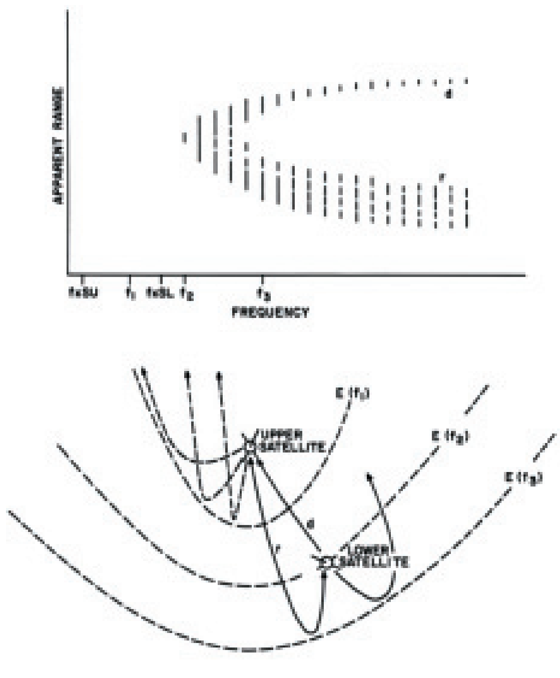

Figure 1. Rays can be traced with the Haselgrove equations to show that O- and X-mode rays, at some frequency, f_1, radiated isotropically by an upper satellite in the topside ionosphere, are contained inside a caustic envelope $\mathrm{E}(f_1)$ that opens upward. There is some higher frequency, f_2, which is the lowest frequency that can reach a lower satellite. At still higher frequencies, such as f_3, a direct ray (d) and a reflected ray (r) can reach the lower satellite, as observed during a rendezvous of the ISIS-I and ISIS-II satellites when their sweeps were fortuitously synchronized. The result is an ionogram pattern like the one shown in the top part of the figure.

and hence the total time-domain pulse shape. In analysis of propagation between the ISIS sounder spacecraft in the slow Z mode, this technique was used to show that ray optics inherent in the Haselgrove equations were inadequate for explaining the observed received pulse shape, and that scattering appeared to be involved [25]. Investigation of the wave phase along upper-branch O- and X-mode rays connecting a ground HF transmitter to the ISIS-II satellite provided information about the range of latitudes for which smooth-ionosphere modeling was sufficient for explaining constructive interference effects, such as the Faraday fading [28].

4. Haselgrove Equations versus Simpler Schemes of Ray Tracing

The Haselgrove equations are applicable to research on spatially complex three-dimensional space plasmas. The Haselgrove equations are especially useful for the computation of long EM ray paths, over which wave packets may encounter different gradients of refractive index in physical space, as well as wave-mode boundaries in wave-vector space. However, there are some areas of ionospheric ray tracing where a different, simpler method is preferred. One such area is electrostatic waves. On account of their spatial and temporal dispersion, electrostatic waves tend to have ray lengths that are small compared with gradient scale lengths in the propagation medium. Electrostatic wave analysis has therefore often been treatable with simplifications of the ray equations. As already mentioned, wave-particle interactions produce electrostatic whistler-mode propagation near the oblique resonance cone [12]. The resonance cone is a singularity in a part of **k**-vector space where some care needs to be exercised to successfully integrate the Haselgrove equations. In this case, it has been found that two-dimensional ray paths can be computed simply with the direct application of Snell's law of refraction. The essential geometry of electrostatic whistler-mode rays was investigated in this way for VLF saucers [29-31] and for auroral-latitude hiss [32], without reference to the Haselgrove equations.

There have been studies of EM rays in which a comparatively simple treatment in two dimensions has been able to describe the physics of radio-wave propagation directly in geospace magnetoplasma. When the principal axes of space plasmas – i.e., the magnetic field direction and its gradient and/or the density gradient – are coplanar with the wave-normal direction, the application of Snell's Law speeds the uncovering of the essential features of propagation. Indeed, the reduction of the Haselgrove equations to Snell's Law was pointed out by Haselgrove when the Haselgrove equations are written in Cartesian coordinates [2]. To illustrate this, note the simplifications of ray solutions obtained in studies of ducting. Ducting is radiowave propagation guided along magnetic-field-aligned enhancements or depletions of density. The efficiency of HF ducting along magnetic lines between conjugate points [33] has been researched with ray-optics techniques. Ray tracing with the Haselgrove equations has been applied to the investigation of ducted EM propagation to explain the apparent multiplicity of paths that are available to ducted signals when the emitter and receiver are inside a duct [34].

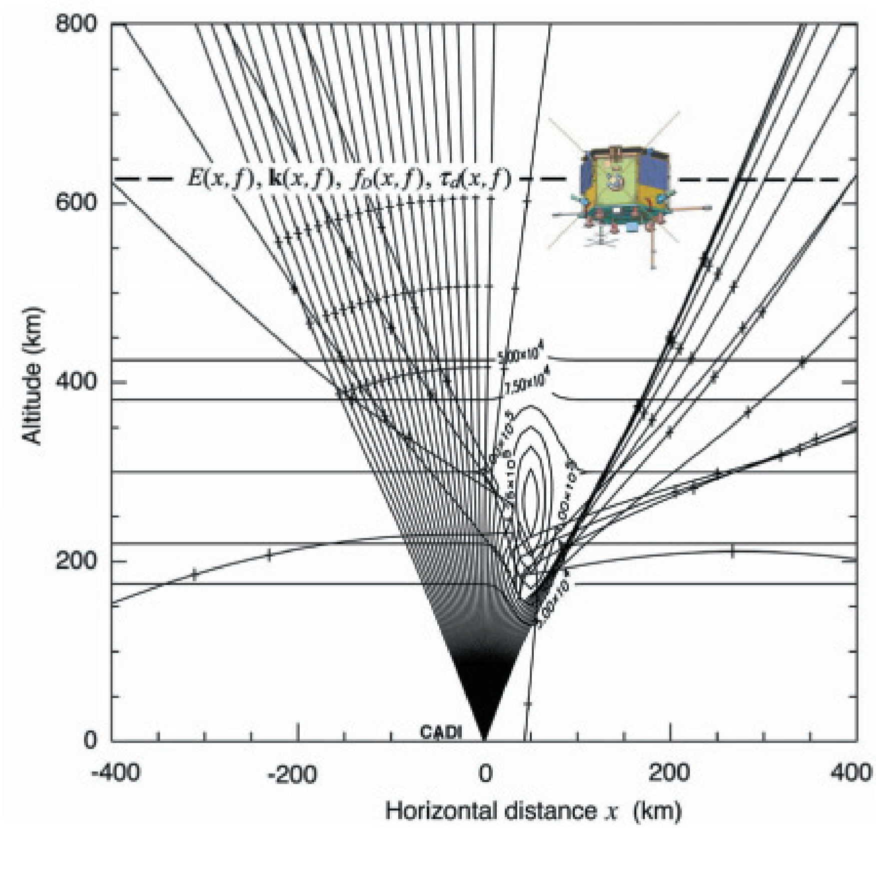

Figure 2. Rays traced from a Canadian Advanced Digital Ionosonde (CADI) are expected to show the refractive effects of ionospheric structure, such as this F-region density enhancement. In the Enhanced Polar Outflow probe (e-POP) mission, the e-POP Radio Receiver Instrument on the CASSIOPE spacecraft will measure the parameters of waves from the CADI in the topside ionosphere.

EM and electrostatic propagation has also been simply explained by combining the relevant dispersion relation with the graphical Poeverlein construction technique [3]. Electrostatic-wave resonances observed with the topside sounders were explained using hot-plasma theory and the two-dimensional Poeverlein construction [35]. Back to ducting, the co-planarity condition was employed to analyze the detection by ground radars of ducted Langmuir waves produced in ionospheric heating [36]. The Poeverlein technique has been applied to ducted Z-mode observations over short distances between a transmitter and a receiver in the ionosphere[37, 38].

5. Recent and Future Applications of Ray Tracing

The Haselgrove equations and similar schemes have continued to be an important tool for analyzing the propagation of radio waves of spontaneous origin. In this issue of the *Radio Science Bulletin*, Kimura [9] provides a review of work done in the twentieth century on spacecraft observations of whistler-mode emissions in the Earth's ionosphere. The accompanying paper by Walker [39] discusses the interpretation of whistler-mode waves recently observed on spacecraft in the planetary magnetospheres, and of waves generated nonlinearly in the Earth's ionosphere by HF heaters.

Looking to the future, ray-tracing procedures will be an important tool for the interpretation of observations made in the upcoming Enhanced Polar Outflow Probe (e-POP) satellite mission [40]. It is proposed to use propagation through the ionosphere at high frequency to image dynamic structures in the F region. As illustrated in Figure 2, various transmitted-wave parameters measurable at low Earth orbit, such as the electric field, E; the direction of propagation, $\mathbf{k}$; the Doppler frequency shift, f_D; and the signal delay, τ_d; will be combined to deduce the shapes of ionospheric structure in the F region below the spacecraft. In preparation for e-POP, the Haselgrove equations have already been applied to explain signal amplitudes and fade effects on transionospheric propagation observed on the ISIS-II spacecraft [28, 41].

Past research in other areas of e-POP objectives indicate that the e-POP radio-science agenda will continue to need the Haselgrove equations for those areas, as well. The explanation of ionosonde or other transmitter echoes returned by the irregular high-latitude ionosphere has sometimes required establishing the comparative importance of large-scale gradients and total reflection. The Haselgrove equations have been employed in studies of backscatter echoes to show that O- and X-mode waves can be refracted so that propagation at the region of scatter is perpendicular to the magnetic field. This approach has been used for density structures moving over ground ionosondes [42], and for intra-ionospheric backscatter observed by orbital sounders [26]. The Haselgrove equations were also used to explore the role of ducting in preparing heater waves for participation in nonlinear processes at their height of total reflection [43].

The attractive simplicity of the ray equations in two dimensions – say, for ducting – has to be weighed against the potential of three-dimensional analysis [44], for opening up new effects or widening understanding of propagation from sources such as ground-based ionosondes or ionospheric heaters [43]. There have been comparatively few investigations of three-dimensional ray tracing, but one senses that new discoveries in space physics from such facilities as coherent-backscatter radar, ionospheric sounding, and ionospheric heating await us when the three spatial dimensions in magnetoplasmas are retained.

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A Review of Whistler-Mode Ray-Tracing Techniques Originated from the Work by J. Haselgrove

Iwane Kimura

This short review is intended to appreciate Dr. J. Haselgrove's original invaluable work in 1954 [1] on the technique of ray tracing using digital computers. My long research career depended greatly on her through my ray-tracing work. I herewith recall my ray-tracing work, done mainly in the VLF range.

When I was an undergraduate student in Kyoto University, in preparation for a graduation thesis in 1954, Prof. K. Maeda, my boss, asked me to read a paper on the whistling atmospherics written by L. R. O. Storey [2]. His discovery of the theoretical interpretation of the whistlers – which suggested the existence of abundant plasmas in the space outside the so-called ionosphere – gave me a big surprise, as the beginning of a new space age. On the other hand, because he did qualitatively explain the whistler ray paths, propagating from one hemisphere to the other nearly along geomagnetic field lines, during the following years as a graduate course student I was encouraged to do ray tracing to see what the real ray paths looked like. At that time, I found the paper by Haselgrove [1]. Her algorithm for ray tracing was developed to perform numerical integration of the differential equations by using a digital computer. This was done for four parameters: radial distance (r), the co-latitudes (θ) of the ray path, and the radial and co-latitudinal components of the wave normal vector ($\mathbf{v}$) in a meridian plane (in the two-dimensional case). However, for me it seemed very difficult to use her algorithm, because we had no digital computers available in Japan. I therefore rather took a different way, namely a graphical method, based on Fermat's Principle.

Our ray tracing in a geomagnetic meridian plane was thus composed of two steps. Firstly, I used the fact that the dip angle of the dipole field is constant at any radial distance at a fixed geomagnetic latitude in the polar coordinate system. If we thus assume that the dip angle is constant within a narrow latitudinal range, the ray path can be governed by a simple Snell's law in the polar coordinates. As the second step, at the boundary of the narrow latitude range, the wave normal will change its direction due to the change of the dip angle. The change of ray path at the sharp boundary can thus be determined by another Snell's law, based on Fermat's Principle. The final ray path was then traced according to the fact that the relation between the wave-normal direction and the ray direction was theoretically known [2]. The Snell's laws to be used in these two processes were graphically drawn in advance, and a combination of these processes was alternately applied to get a ray path. The ray tracing was done in the dipole geomagnetic field. It took much time to calculate one ray path of a whistler from one hemisphere to the other by this method, due to the division of the total latitudinal range into small sectors. In any case, we could have several ray paths, starting from different starting latitudes at the top (assumed to be located at an altitude of 300 km) of the ionosphere, above which an exponentially decreasing electron-density profile was adopted. As a result, we [3, 4] could calculate several ray paths of whistlers, as Storey's hypothesis predicted. High accuracy in the calculation could not be anticipated, due to the fact that the calculation was made by a semi-manual process, using graphs with a limited number of calculation steps. However, it was said that this paper was the first ray tracing of whistlers in the world.

In 1964, Prof. Helliwell invited me to the Radio Science Laboratory of Stanford University. There, I recognized that Yabroff had done ray tracing of whistlers by using a digital computer [5]. His ray-tracing program was three dimensional. It had simultaneous integrations of the seven differential equations for seven parameters, namely, the three coordinate parameters in the spherical coordinate system (r, θ, and φ), the three components of the wave-normal vector ($\mathbf{v}$), and the propagation time (t), based on Haselgrove's technique [1]. He used the electron-density profile that we used in our graphical ray tracing [3]. We could thus check the roughness, or accuracy, of our work. It turned out that the results of our manual and graphical calculations were not accurate enough, as expected, compared with those calculated by a digital computer, but were qualitatively acceptable.

So far, the ray tracing of whistlers had been done in the plasmasphere, only taking account of electrons. At

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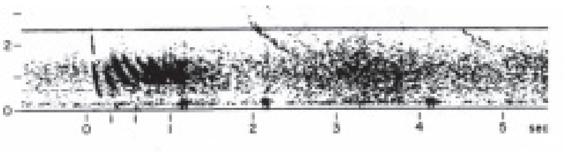

Figure 1. SP whistlers observed by the Alouette satellite.

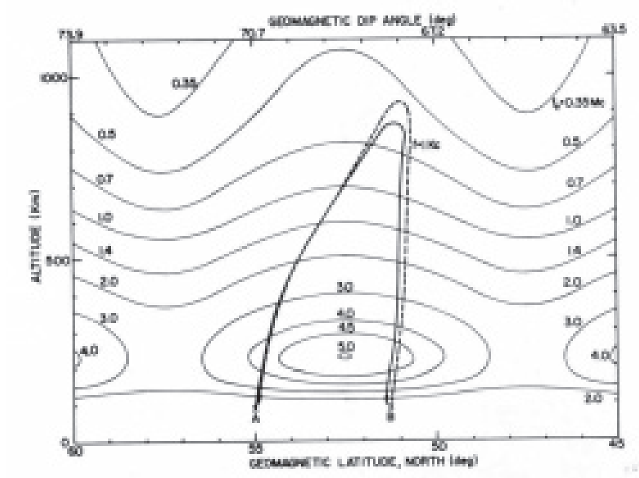

Figure 2. Kimura's [13] results of ray tracing representing echoing SP whistlers.

Stanford, I was requested to do ray tracing using Yabroff's computer program – which was based on Haselgrove's technique [1, 6] – taking account of the effects of positive ions: protons, alpha particles, and oxygen ions, which are the main ionic constituents in the plasmasphere, in and above the ionosphere. Around that time, Carpenter et al. [7] found a new phenomenon: whistlers trapped below the protonosphere, discovered by the Alouette satellite. Smith and Brice [8] theoretically studied propagation in multi-component plasmas, based on Hines' paper [9]. These phenomena and theoretical studies predicted that there might be interesting ray paths obtained by taking account of the effects of positive ions [10].

My work on ray tracing was to consider how to include the effects of multi-ions in the ray-tracing program, based on the diffusive equilibrium plasma model [11] as the background. It was found that if the refractive index was simply expressed by Stix's formula [12], the ray-tracing program did not become too complex, even with the inclusion of ions. As was expected, the results of ray tracing could show the reflections of ray paths at the lower hybrid resonance (LHR) condition by the positive ions. A distinct difference arising from the effect of positive ions is that the refractive index becomes finite for the wave-normal direction perpendicular to the background magnetic field line, and then the ray can cross the magnetic field line (which is called the LHR condition). On the other hand, when only the effect of electrons is considered, the refractive index becomes infinity inn this condition, so that the ray cannot cross the background magnetic field. The sub-protonospheric (SP) whistlers, as named by Carpenter et al. [7], could then be clearly ascertained by this ray tracing, as shown in Figures 1 and 2.

This ray tracing also showed that there were ray paths propagating toward higher altitudes as a result of reflecting several times at lower altitudes due to multiple lower-hybrid resonance reflections, as shown in Figure 3. This phenomenon was later found by OGO-I satellite observations, and these were called magneto-spherically reflected (MR) whistlers [14], as shown in Figure 4.

The inclusion of positive ions also suggested the possibility of the existence of trapping of rays within the ionospheric region due to the LHR reflection. This was called an "LHR duct" within the ionosphere [15] as shown in Figure 5, which was calculated by Kimura (introduced in [16, 17]).

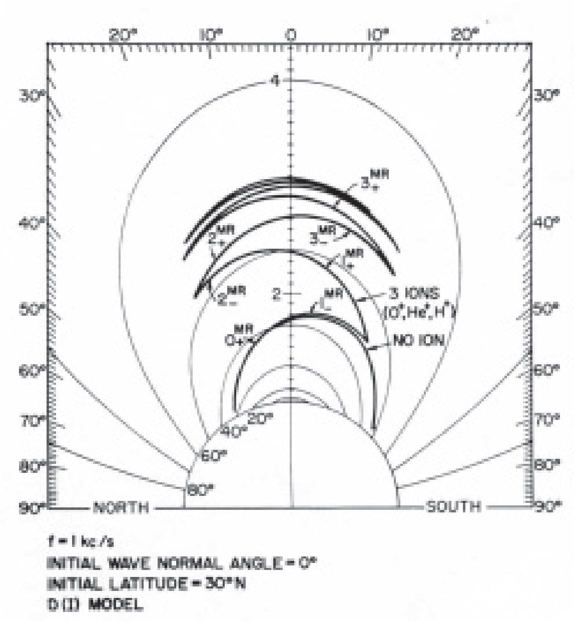

Figure 3. Magnetospheric reflections (MR) due to the ray path crossing the geomagnetic field line under the LHR conditions.

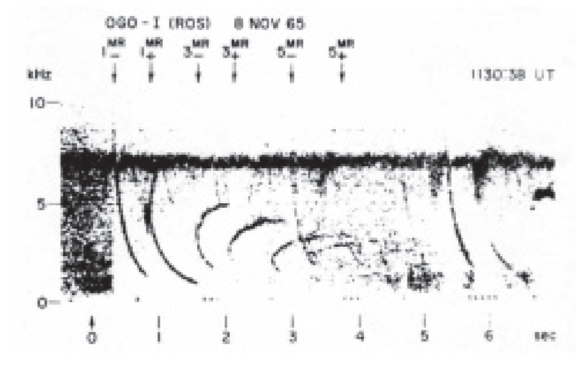

Figure 4. MR whistlers observed by the OGO-I satellite.

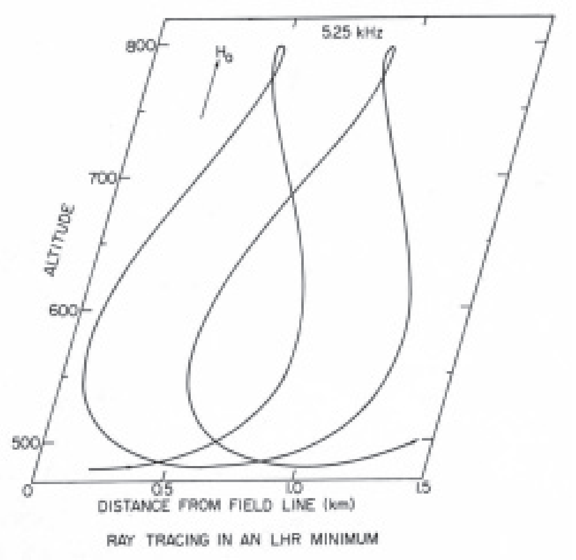

Figure 5. An LHR duct produced at the ionospheric height.

As mentioned above, my ray-tracing program developed at Stanford University, taking into account the effect of positive ions, generated many new findings. (Several such results were reviewed in a paper by Kimura [16]).

The three-dimensional ray-tracing program based on Haselgrove's technique in a diffusive-equilibrium plasma model could be extended to several modifications, such as ray tracing of VLF waves in the IGRF model (1985) instead of the dipole model [18]. The IGRF model has been thought to be more realistic than the dipole model for ray tracing. However, in the IGRF model, magnetic field lines are determined by field-line tracings. Also, the plasma densities in the diffusive-equilibrium model are defined along a magnetic-field line. Therefore, in this case, to do a ray trace, the magnetic-field-line tracing should be made in advance, for a pre-assigned mesh (or grid) homogeneously distributed in the plasmasphere. This technique seems rather tedious, but it is necessary to do such ray tracing when we investigate whistler-mode wave phenomena observed by satellites. It is also necessary when we compare the quantities observed on satellites, such as the wave-normal direction and the propagation delays from their source, with those theoretically calculated in the diffusive-equilibrium model (as will be mentioned later).

Another extension of the program was ray tracing in the plasma with the effect of plasma temperature (Hashimoto et al. [19]). In their paper, an electrostatic approximation of the refractive index and, moreover, full dispersion in a hot plasma were used for ray tracing to explain electrostatic cyclotron harmonic waves and Z-mode electromagnetic waves in the magnetosphere.

Finally, I have to introduce an interesting application of ray tracing for ground-based VLF transmitter signals. In 1989, a Japanese scientific satellite, Akebono (EXOS-D), was launched. We installed several VLF receivers with orthogonally-crossed three-loop antennas (with a diameter of 60 cm), and two pairs of long dipole antennas of 60 m length, on this satellite. In particular, PFX (Poynting flux) receivers could detect the waveforms of ground-based Omega signals at 10.2 kHz, along with their delay time from the source to the satellite and their wave-normal direction. The latter was determined by the Means method [20], by using the three components of their wave magnetic field and two components of their electric field. The direction of the wave normal and the delay time were the quantities to be calculated by ray tracing. Therefore, by comparing these quantities obtained by Akebono observations with those calculated by ray tracing, the global electron-density profile could be determined. For this study, we first assumed a plasma-density profile defined by a diffusive-equilibrium model with variable parameters. In the process of data comparison, we looked for the best combination of variable parameters by the least-mean-square method. This trial was quite successful, and by just one trajectory passing over one Omega station (for a time period of about 30 to 60 minutes), we could determine a global electron-density profile (Kimura et al. [16, 21]). This means that we could determine the global electron-density profile with a time scale of less than one hour. We thought that this technique would really be the most useful application of the ray-tracing technique. However, to our regret, the Omega navigational system function was ended on September 30, 1997, by the replacement with the GPS system. Our data acquisition of Omega also stopped on that day, although the Akebono satellite is still alive and sending data to the ground.

I know that there was plenty of work by other authors on ray tracing of VLF and HF waves in the plasmasphere and the ionosphere that were all based on Haselgrove's technique. Our computer program can also be applied to HF, VHF, and to a much higher-frequency range, by selecting an appropriate mode for the refractive index. I am now still using the ray-tracing program at my home, using a personal computer. I use it for HF radio propagation in an arbitrary electron-density distribution, constructed from numerical electron-density data in the ionosphere. For this case, the derivatives of the plasma density with respect to the coordinates are necessary for ray tracing. We have therefore modified the computer program to calculate the derivatives numerically along the ray-path calculation.

Conclusion

I have mostly reviewed here the results of ray tracing in the VLF range. However, there have been a great number of new findings observed by satellites, most of which could be quantitatively explained by the results of ray tracing. Several additional modifications to the ray-tracing program were also used, as mentioned in this review. There have been numerous examples of ray tracing also done in the frequency range from ELF up to VHF in the ionosphere and plasmasphere. Moreover, this has been done even for the

GPS frequencies, to compensate for a navigational error due to the plasmas existing along the ray path from the satellite to an arbitrary point on the ground. These are all based on the path-integration technique using digital computers, initially studied by Dr. J. Haselgrove in 1954. We are very much indebted to her invaluable work. Besides the path-integration algorithm, the ray-path programs developed by us and introduced here were fortunately all our original programs. We are very pleased to be able to have contributed much in this research field during these 50 years.

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Ray Tracing in the Magnetosphere

A.D.M. Walker

Abstract

Haselgrove's method of ray tracing has been widely used in ionospheric and magnetospheric physics since it was first developed more than fifty years ago. The method is reviewed in this paper. The reciprocal properties of the refractive-index and ray surfaces are discussed, and used to derive the ray-tracing equations. It is shown that Haselgrove's method of deriving the equations can be understood as the mathematical representation of Huygens' construction in Geometrical Optics. The relationship between group velocity and the velocity of energy propagation is outlined. Methods of finding changes in intensity as a result of losses, and also as a result of convergence or divergence of the rays, are outlined. The importance of the method is illustrated by a review of its application to a variety of problems of radiowave propagation in the magnetosphere. This shows the value of the method, which has been in continuous use since it was first presented to the ionospheric community.

1. Introduction

At the Institute of Physics conference on the physics of the ionosphere held in London in 1954, a young Cambridge physicist, Jennifer Haselgrove, presented a somewhat abstruse paper on how to trace rays in an anisotropic medium such as the ionosphere [1]. This was the time when electronic computers had first become available to scientists, and it had become possible to contemplate calculations that had previously been intractable and unattainable. The first paper on the technique in a refereed journal [2] appeared in 1957, and the current year, 2007, is the fiftieth anniversary of the technique.

In this paper, we first provide a critical review of the ideas fundamental to ray tracing. We discuss the nature of Geometrical Optics in anisotropic media, including the proper use of Huygens' principle and the meaning of Fermat's principle of least time. We then provide a simple and accessible derivation of the ray-tracing equations. We discuss the relationship of ray tracing to energy propagation, as well as changes in intensity due to losses, and also convergence and divergence of rays. Finally, we discuss some of the many papers in magnetospheric physics that have made use of the technique, concentrating on recent work in the past three years but not omitting some of the important historical works.

2. Geometrical Optics in Uniform Anisotropic Media

In any medium that is sufficiently slowly varying, i.e., one in which the properties do not change significantly over one wavelength, propagation can often be usefully treated by the methods of Geometrical Optics. In this section, we discuss the nature of Geometrical Optics in a uniform anisotropic medium as a preliminary to discussing propagation in a slowly varying medium.

2.1 Constitutive Relations and Dispersion Relations

The physics of a magnetoplasma are governed by Maxwell's equations, together with constitutive relations relating $\mathbf{D}$ to $\mathbf{E}$ and $\mathbf{H}$ to $\mathbf{B}$. The constitutive relations are generally nonlinear because of the magnetic forces $q\mathbf{v}\times\mathbf{B}$ but, if we assume that the wave disturbance is small, the terms involving products of the field variables can be ignored and the equations linearized. This leads to a set of equations governing the propagation of linear electromagnetic waves in such a plasma.

For plane, linear waves that are assumed to vary in time as

$$\exp\{i\Phi\} \equiv \exp\{i[\mathbf{k}\bullet\mathbf{r} \pm \omega\mathbf{t}]\}, \qquad (1)$$

where Φ is the phase, the constitutive relation is a tensor relationship. In all practical circumstances, the plasma is nonmagnetic in the sense that

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$$\mathbf{H} = \mathbf{B}/\mu_0 , \tag{2}$$

where μ_0 is the permittivity of free space. The electrical properties of the medium are anisotropic, and the relation between **D** and **E** is more complicated. In Cartesian tensor notation [3], the constitutive relation may be written as

$$D_i = \varepsilon_{ij}(\omega, \mathbf{k}) E_j \cdot \tag{3}$$

The dielectric tensor, ε_{ij}, is, in the most general case, a function of both ω and $\mathbf{k}$. However, in many cases it is a function of frequency, ω, and only the direction of $\mathbf{k}$. It is independent of the magnitude of $\mathbf{k}$. In particular, this is true in a cold plasma, such as that which exists in most of the magnetosphere. In warm plasmas, the phenomenon of spatial dispersion occurs, and the dielectric tensor is also an explicit function of the wave vector, $\mathbf{k}$. Expressions for the elements of the dielectric tensor in various conditions are given by many authors [4-6].

In the absence of losses, ε_{ij} is Hermitian, so that

$$\varepsilon_{ij} = \varepsilon_{ji}^{*} \cdot \tag{4}$$

When the wave varies in space and time as in Equation (1), the operators in Maxwell's equations take the form

$$\nabla \equiv i\mathbf{k} , \tag{5}$$

$$\frac{\partial}{\partial t} \equiv -i\omega \cdot$$

If **H** and **D** are eliminated using the constitutive relations, we get a set of simultaneous homogeneous algebraic equations for **E** and **B**. The condition for these to be self-consistent is that the determinant of their coefficients is zero. These coefficients depend on the elements of the dielectric tensor, and therefore on ω and **k**. This relationship can be formally written as

$$G(\mathbf{k}, \omega) = 0 \cdot \tag{6}$$

For a fixed frequency ω, this is a relationship between the three components of the wave vector, **k**. The wavelength is given by $2\pi/k$, and the direction of propagation by the direction of k. Frequently, the dispersion relation is expressed in terms of the refractive-index vector

$$\mathbf{n} = c\mathbf{k}/\omega \cdot \tag{7}$$

2.2 Plane Waves and Wave Packets

Plane waves vary in space and time according to Equation (1). A more general signal can be represented by a Fourier synthesis of such plane waves. Consider a wave packet that has originated at a distant point $\mathbf{r} = 0$, and that is limited in time and space. At an instant $t = 0$, a field component, $f(\mathbf{r}, t)$, in the wave can be Fourier analyzed in space. It is then represented by the three-dimensional spatial Fourier integral

$$f(\mathbf{r}, 0) = \int_{-\infty}^{\infty} F(\mathbf{k}) e^{i\mathbf{k}\bullet\mathbf{r}} d^3\mathbf{k} . \tag{8}$$

As time advances, each plane wave in the spectrum develops according to Equation (1), so that

$$f(\mathbf{r}, t) = \int_{-\infty}^{\infty} F(\mathbf{k}) e^{i(\mathbf{k}\bullet\mathbf{r} - \omega t)} d^3\mathbf{k} . \tag{9}$$

The choice of the minus sign for ω is for reasons of causality, so that the wave is propagated away from the source. The frequency, ω, of each component plane wave in the spectrum is determined from k through the dispersion relation, so that in general there is a range of values of ω in the spectrum.

When the wave packet is localized, the evaluation of integrals of this type can be done by asymptotic methods, such as the method of steepest descents or Rayleigh's method of stationary phase [7]. The latter method can be understood physically by noting that the component plane waves in the spectrum of Equation (9) in general have different phases and directions of propagation and interfere destructively. Only where the component plane waves remain in phase over several wavelengths does constructive interference take place. This defines the position of the wave packet, and occurs where the phase, Φ, has a stationary value with respect to variations in **k**. The condition for this is that the rate of change of the phase with respect to each component of **k** must be zero:

$$\nabla_k \Phi = 0 \cdot \tag{10}$$

This leads to

$$\mathbf{r} = t \nabla_k \omega , \tag{11}$$

so that the wave packet advances with a velocity $\nabla_k \omega$, which is called the group velocity, $\mathbf{V}_G$. Notice that in an anisotropic medium, this is not $d\omega/dk$, since $\nabla_k \omega$ is not in general parallel to **k**. The quantity $d\omega/dk$ is the component of $\mathbf{V}_G$ parallel to **k**. Only in isotropic media is the magnitude of the group velocity equal to $d\omega/dk$.

An infinite plane monochromatic wave carries no information. Only changes in the nature of such a wave can transmit information. Such changes are propagated at the group velocity. Any feature propagated at the group velocity is called a signal. If a signal is switched on abruptly, the initial disturbance, propagated at the group velocity, is called the signal front.

2.3 Wave-Vector, Ray, and Group Velocity Surfaces

2.3.1 The Wave-Vector Surface

For a fixed frequency ω, the dispersion relation of Equation (6) is a relationship between the three components of the vector **k.** Each value of ω defines a surface in **k** space called the *wave-vector surface*. This is often normalized as in Equation (7). The corresponding surface in **n** space is the *refractive-index surface*.

In **k** space, there is a family of such surfaces with ω as a parameter. The frequency is a function of **k** through Equation (6), and the normal to any surface of constant ω is the gradient of ω in k space. However, $\nabla_k \omega$ is the group velocity, and so we obtain a well-known result. For a particular value of **k** and ω, the group velocity is perpendicular to the wave-vector surface corresponding to ω, at the point where **k** intersects it. Thus, $\omega(\mathbf{k})$ serves as a potential function for the group velocity.

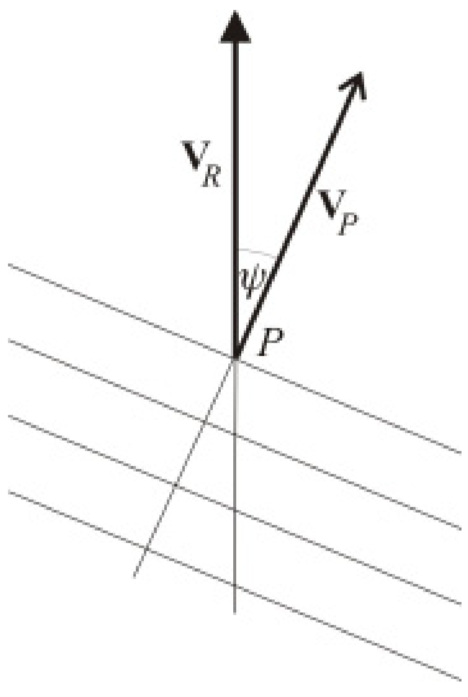

Figure 1. Illustrating a sequence of wavefronts moving in the direction of the phase velocity, $\mathbf{V}_P$. The ray velocity, $\mathbf{V}_R$, makes an angle ψ with the phase velocity.

Some authors use a surface that represents the surface swept out by the tip of the phase-velocity vector for all directions of propagation. This has no value in ray tracing, and when this phase-velocity surface is erroneously stated to represent the shape of a wavefront emerging from a point source [8-10], it is dangerously misleading. The phase-velocity surface is not the reciprocal surface to the wave-vector surface in the Hamiltonian sense. The correct reciprocal surface is the ray surface described in the following section, and it is the ray surface that represents the shape of a wavefront from a point source. It is obvious that since the tangent planes to the phase-velocity surface are not normal to the wave vector, the phase-velocity surface cannot represent wavefronts of a continuous wave.

2.3.2 The Ray Surface

If a point source radiates, then the signal moves out from it in the ray direction. Consider Figure 1. A sequence of wavefronts is illustrated by a series of parallel lines. The phase-velocity vector, $\mathbf{V}_P$, is normal to the wavefronts. The vector labeled $\mathbf{V}_R$ is parallel to the group velocity $\mathbf{V}_G$, which makes an angle ψ with the wavefronts. The signal arriving at P has traveled from the source along a ray that is in the direction of the group velocity. The intersections of the wavefronts with this ray travel along the ray with a speed given by

$$V_R = V_P / \cos\psi \cdot \tag{12}$$

The vector $\mathbf{V}_R$, with magnitude $V_P \sec\psi$ and with the direction of the group velocity, is called the ray velocity.

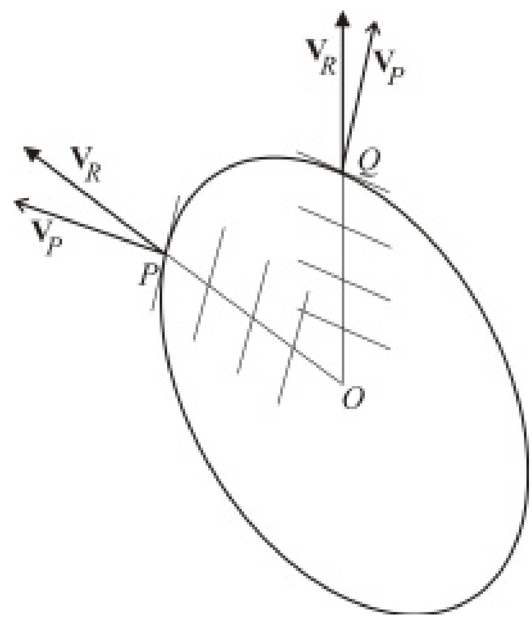

Figure 2. The ray surface (see text for an explanation).

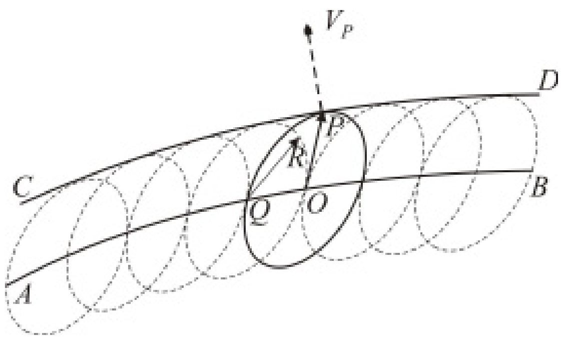

Figure 3. Huygens' Principle (see text for an explanation).

Now consider a wave originating from an isotropic point source. The rays all diverge from this source. After a time t, the intersection of any such ray with a wavefront emerging from the source has moved a distance $V_P t$. Figure 2 shows two such rays with several wavefronts represented by parallel lines. The wavefronts at P and Q have moved the same distance from the source. The envelope of all such plane wavefronts is the surface shown, which has a radius proportional to the ray velocity. This surface is called the *ray surface*. It represents the shape of wavefronts emerging from a point source. Since the phase velocity $\mathbf{V}_P$ is normal to the wavefronts, it is normal to the ray surface.

The wave-vector surface – or, equivalently, the refractive-index surface – and the ray surface thus have reciprocal properties. For a given direction of the wave vector, the corresponding ray direction is normal to the wave-vector surface; for a given direction of the ray, the corresponding wave vector is normal to the ray surface.

2.3.3 The Group-Velocity Surface

We can also draw a surface called the group-velocity surface. This is the surface traced out by the tip of the group-velocity vector as the direction of propagation is changed. A signal front or a short pulse emitted by a point source would spread out in space in this shape.

In a magnetoplasma, there is a very wide range of topological forms that the various surfaces can take. They may be classified in parameter space using a diagram called the Clemmow-Mullaly-Allis (CMA) diagram [11, 12]. An atlas of such surfaces has been presented for a cold plasma [13-15].

Figure 4 illustrates an example of the complexity that such surfaces can have. It represents the various surfaces for the whistler mode. In each of the four panels, the magnetic field is directed to the right along the x axis. All the surfaces have rotational symmetry about the direction of the magnetic field.

Figure 4a shows the refractive-index surface (or normalized k surface). In this diagram, a vector from the origin touching the surface has a length representing the magnitude of the refractive index for propagation in the radial or wave-normal direction.

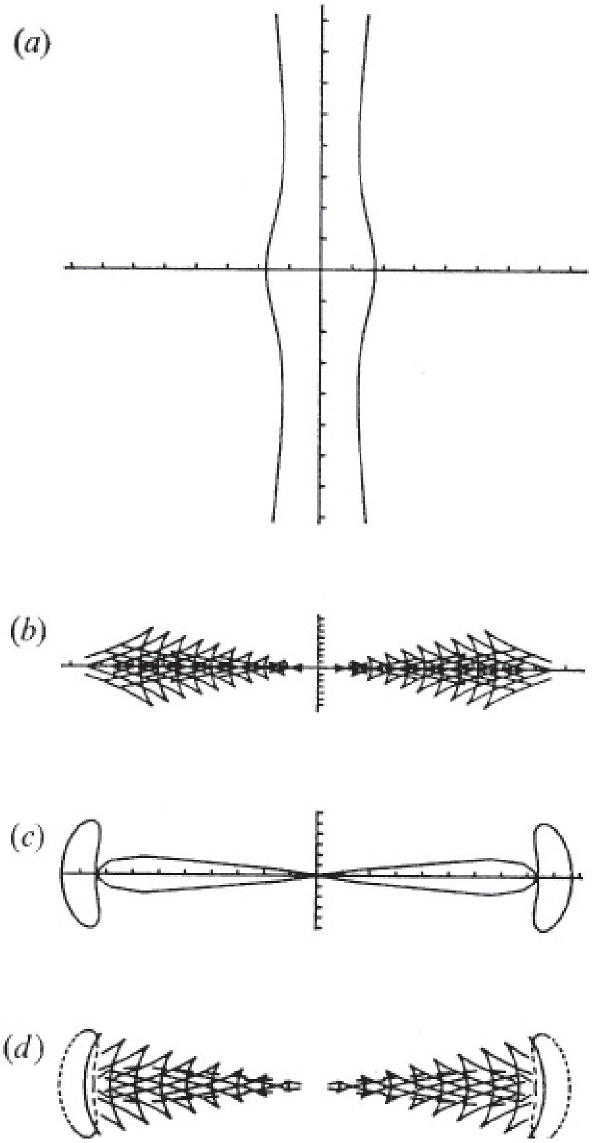

Figure 4. The characteristic surfaces for the whistler mode: $X \equiv \frac{\omega_P^2}{\omega^2} = 100$; $Y \equiv \frac{\omega_H}{\omega} = 5$. *The magnetic field is directed towards the left. (a) The refractive-index surface. (b) A set of wavefronts with the shape of the ray surface, representing whistler waves originating continuously from a point source. (c) The group-velocity surface. (d) A set of wavefronts following a signal front, representing the signal that originates from a point source that is abruptly switched on*

To understand the ray surfaces shown in Figure 4b, we consider the refractive-index surface shown in Figure 4a. If we first consider propagation parallel to the field, we see that the normal to the refractive-index surface (which is the ray direction) is parallel to the wave normal. If we now continuously increase the angle between the wave normal (in the radial direction) and the magnetic field (the *x* axis), we see that the angle between ray and magnetic field also increases initially, although ray and wave normal do not remain parallel. As the wave-normal angle increases further, the ray angle reaches a maximum, after which it decreases. Further increase of the wave-normal angle allows the ray direction to again become parallel to the magnetic field, and thereafter to make a negative angle with it. The refractive-index surface is asymptotic to a double cone. This cone is defined by the angle at which the refractive index becomes infinite. At this angle, both phase and group speeds become zero: this is a resonance. For angles greater than this critical angle, the wave is evanescent and there is no propagation. If we consider the components of **k** parallel and perpendicular to the field, we see that for a given range of $k_{\|}$ there are two values of $k_{\perp}$, the magnitude of $\mathbf{k}_{\perp}$. The smaller of these corresponds to a wave that is predominantly electromagnetic, with elliptical polarization nearly perpendicular to **k** (for propagation parallel to the field, the polarization is circular); the larger corresponds to an electrostatic wave with electric field almost parallel to **k**. The transition from one to the other occurs for the minimum value of $k_{\|}$ at an angle known as the Gendrin angle*.

Figure 4b shows the ray surface traced out by the tip of the ray-velocity vector. To form the surface, we plot the ray speed against ψ, the angle between the ray and the wave vector. When it reaches the maximum angle, corresponding to a point of inflection in the refractive-index surface, the ray surface has a cusp. For wave-normal angles greater than this, the phase speed approaches zero. However, the ray speed is given by Equation (12), and $\cos\psi$ also approaches zero at the resonance cone. The limit is such that the ray speed approaches infinity at the resonance cone. This is because it represents the speed at which the intersection of the wavefront and the ray direction moves along the ray. Since the angle between wave normal and ray direction approaches 90º, this intersection moves with a speed approaching infinity, even though the group velocity, representing the velocity of energy propagation, approaches zero. Figure 4b shows a succession of ray surfaces, with radii corresponding to the distance the wave has progressed over an equally spaced set of times. This represents the appearance of waves from a point source isotropically radiating whistlers in all directions. The locus of the cusp in the surface is a caustic surface [16]. The resonance cone is defined by the angle at which the ray speed goes to infinity, and lies inside this caustic surface.

The group-velocity surface is shown in Figure 4c. If a point source is abruptly switched on, the initial disturbance spreads out at the group velocity. The region behind the signal fronts in this surface is populated by wavefronts with the shape of the ray surface, as illustrated in Figure 4d. Examples of a wide variety of such surfaces are given in the papers by Walker cited above.

2.4 Huygens' Principle in Anisotropic Media

2.4.1 Huygens' Principle

Huygens' principle in Geometrical Optics is encountered by every student of elementary physics. It states that every point on a wavefront can be regarded as a point source of secondary wavelets that are propagated according to the dispersion relation of the medium. In general, these wavelets interfere destructively with each other. Only where they interfere constructively is the signal appreciable. After a time *t*, the position of the wavefront is represented by the locus on which constructive interference takes place. We see that for an anisotropic medium, the wavelets must have the shape of the ray surface.

Consider Figure 3. At time $t = 0$, a wavefront is located at *AB*. Wavelets having the shape of an anisotropic ray surface originate on this wavefront. After a time *t*, they have reached the positions shown. Their envelope now represents the position of the new wavefront *CD.* Clearly, the phase-velocity vector, and hence the wave vector, remain normal to the wavefronts.

2.4.2 Fermat's Principle of Least Time

In Figure 3, the portion of the wavelet originating at *O* that interferes constructively to produce the new wavefront has reached position *P* in time *t*. Consider an adjacent wavelet originating at *Q*. After time *t*, the portion of this wavefront traveling towards *P* has reached position *R*, and has not yet reached the new position of the wavefront. Clearly, the ray *OP* is the path that requires the shortest time to reach point *P* on the new position of the wavefront. This is Fermat's principle of least time: the ray travels along the path that minimizes the time of travel of the wavefront.

3. Theory of Ray Tracing

3.1 Slowly Varying Media and the Phase-Integral Approximation

Ray tracing is based on the assumption that the medium is slowly varying. By this it is meant that over a distance of one wavelength, the properties of the medium do not vary appreciably. The medium is essentially uniform on the scale of a wavelength.

In the slowly varying medium, the quantity $G(\mathbf{k},\omega)$ is a slowly varying function of position, and so $\mathbf{k}$ varies in space. If, at a fixed time, we move a small distance $d\mathbf{r}$, the phase changes by an amount $d\Phi$. If we move along a path through the wave, the total change of phase along the path is

$$\Delta\Phi = \int_{\text{path}} \mathbf{k} \bullet d\mathbf{r} . \tag{13}$$

For harmonic waves, the phase is a single-valued function of position, and the line integral of $\mathbf{k}$ around a closed loop is zero. Thus, $\nabla \times \mathbf{k} = 0$, and Φ acts like a potential function for $\mathbf{k}$, so that

$$\mathbf{k} = \nabla\Phi , \tag{14}$$

and the direction of $\mathbf{k}$ is normal to the surfaces of constant Φ. Such a surface is called a wavefront. We note also that

$$\omega = -\frac{\partial\Phi}{\partial t} . \tag{15}$$

If we use Equation (13), then Equation (1) can be modified so that a field component is represented by

$$f(\mathbf{r},t) = \int_{-\infty}^{\infty} F(\mathbf{k}) \exp\left\{ i \left[\int \mathbf{k} \bullet d\mathbf{r} - \omega(\mathbf{k}) t \right] \right\} d^3\mathbf{k} .$$

For such a field component, if the medium is slowly varying so that the dependence of $F(\mathbf{k})$ on position gives a gradient small compared with the rate of change of the phase, the operators $\partial/\partial t$ and ∇ are still given by Equation (5).

3.2 The Ray-Tracing Equations

3.2.1 Tracing the Ray Path

We present here a very simple derivation of a set of ray-tracing equations, using vector methods to keep the derivation coordinate-free. We follow the path of a wave packet traveling with the group velocity $\mathbf{V}_G$. If the wave packet moves a distance $d\mathbf{r}$ in time dt, then

$$\frac{d\mathbf{r}}{dt} = \nabla_k \omega(\mathbf{r},\mathbf{k}) , \tag{16}$$

where ω is given as a function of k through the dispersion relation of Equation (6):

$$\nabla_k \omega = -\frac{\nabla_k G}{\partial G/\partial\omega} .$$

As the wave packet moves, the wave is refracted, and the conditions in the medium change. Thus, $\mathbf{k}$ must change in magnitude and direction. One method of finding the rate of change of $\mathbf{k}$ is to assume the constancy of frequency. After a time dt, the wave packet has moved a distance $d\mathbf{r}$. The dispersion relation must still hold at the new position. We assume that as we follow the ray, the frequency remains constant, so that $d\omega/dt = 0$. Then,

$$\frac{d\omega}{dt} = \nabla\omega \bullet \frac{d\mathbf{r}}{dt} + \nabla_k \omega \bullet \frac{d\mathbf{k}}{dt} = 0 . \tag{17}$$

If we substitute from Equation (16) for $d\mathbf{r}/dt$, we get

$$\left\{ \nabla\omega + \frac{d\mathbf{k}}{dt} \right\} \bullet \nabla_k \omega = 0 \tag{18}$$

and, since $\nabla_k \omega$ is not zero,

$$\frac{d\mathbf{k}}{dt} = -\nabla\omega(\mathbf{r},\mathbf{k}) . \tag{19}$$

This set of three equations shows how the change in the wave vector with time depends on the gradient of the dispersion relation. This gradient determines the local stratification of the medium and how it affects the wave-normal direction as the wave packet is propagated. As recognized by Haselgrove, it amounts to a generalized form of Snell's law.

When the components are written in an appropriate coordinate system, the two Equations (16) and (19) form a set of six simultaneous first-order differential equations that are suitable for numerical integration. All that is needed is an appropriate dispersion relation. If we know the dispersion relation as a function of $\mathbf{r}$ and $\mathbf{k}$, we can compute its derivatives and advance the equations by a step using a routine for the solution of first-order simultaneous differential equations, such as the Runge-Kutta method.

These are not exactly the same as the set of equations derived by Haselgrove from Fermat's principle of least time. The first equation, Equation (16), follows the path of the ray at the group velocity. Each time step δt advances the ray a distance $V_G \delta t$. If we consider a pencil of rays originating from a point, and trace each ray for a time *t*, we will obtain the shape of the signal front that has been propagated through the medium for that time. Haselgrove's equations are equivalent to advancing at the ray velocity, V_R.

Now, clearly,

$$\frac{\mathbf{k} \bullet \nabla_k \omega}{\omega} = \frac{V_G \cos\psi}{V_P} = \frac{V_G}{V_R} . \tag{20}$$

Thus, a suitable equation to replace Equation (16), so that we follow a wavefront rather than a signal front, is

$$\frac{d\mathbf{r}}{dt} = \frac{\omega \nabla_k \omega(\mathbf{r},\mathbf{k})}{\mathbf{k} \bullet \nabla_k \omega(\mathbf{r},\mathbf{k})} \equiv \mathbf{V}_R . \tag{21}$$

This can be substituted into Equation (17) to find a suitable equation for the advance of **k**. The result is

$$\frac{d\mathbf{k}}{dt} = -\frac{\omega \nabla \omega(\mathbf{r},\mathbf{k})}{\mathbf{k} \bullet \nabla_k \omega(\mathbf{r},\mathbf{k})} \cdot \tag{22}$$

3.2.2 Constancy of Frequency

In the last section, we obtained the second Equation (19) by assuming that the frequency remains constant along a ray. This seems intuitively obvious. However, it is possible to prove that it is constant from the basic assumptions of ray theory. In the context of sound waves, Lighthill [17] provided such a proof. It applies quite generally to magnetohydrodynamic waves, and is as follows.

Using Equation (14), we can write Equation (15) in the form

$$\frac{\partial \Phi}{\partial t} = -\omega(x_i, k_i) = -\omega\left(x_i, \frac{\partial \Phi}{\partial x_i}\right) \cdot \tag{23}$$

If we then take its gradient, we get

$$\frac{\partial^2 \Phi}{\partial x_i \partial t} = -\frac{\partial \omega}{\partial x_i} - \frac{\partial \omega}{\partial k_j}\frac{\partial^2 \Phi}{\partial x_i \partial x_j} \cdot \tag{24}$$

Alternatively, using Equations (14) and (11),

$$\frac{\partial k_i}{\partial t} + V_{G,j}\frac{\partial k_i}{\partial x_j} = -\frac{\partial \omega}{\partial x_i} \cdot \tag{25}$$

The left-hand side of this is just $d\mathbf{k}/dt$, the time rate of change of **k** following a wave packet moving with the group velocity $\mathbf{V}_G$. It is therefore identical with Equation (19), which is thus determined without an assumption of constant frequency. If we substitute the expressions for $d\mathbf{r}/dt$ and $d\mathbf{k}/dt$ into the expression for $d\omega/dt$ given by Equation (17), we see that along the ray,

$$\frac{d\omega}{dt} = 0 , \tag{26}$$

and so ω is constant as the wave packet is propagated.

3.2.3 Haselgrove's Approach

Although they look very different, Equations (21) and (22) are the same as Haselgrove's three-dimensional equations [18]. Haselgrove was working in a very different environment. In 1954, the power of electronic computers was still to be realized. In the Mathematical Laboratory at Cambridge, M. V. Wilkes's group had developed the pioneering British computer, EDSAC. Wilkes himself had begun his career in Appleton's ionospheric group, and several members of that group were pioneers in applying new techniques in computing to physical problems. EDSAC was one of only a small handful of operating scientific computers in the world. Its speed was minute compared with a modern handheld calculator. It had only a few hundred words of "immediate access memory" (RAM), and no analogue of disk storage. It had a human operator rather than an operating system, and programs were written in machine language. Communication between machine and operator was by means of punched paper tape. In such circumstances, it was necessary to be extremely efficient in planning and executing computation. Jennifer Haselgrove was a mathematician whose objective was to produce an elegant and general analysis that would produce a set of equations forming the basis of a suitable computational framework. She notes in her paper, "Some ray paths have been calculated, using the electronic computer EDSAC....Each ray took less than ten minutes of machine time." A similar modern calculation, including graphics, on a laptop computer is in human terms nearly instantaneous.

The approach adopted by Haselgrove was to work in terms of the refractive-index vector, $\mathbf{u} = c\mathbf{k}/\omega$, rather than the wave vector, **k**. She wrote the dispersion relation in the form

$$G \equiv \frac{u}{\mu(\mathbf{u},\mathbf{x})} = 1 , \tag{27}$$

where μ was a refractive-index function of wave-normal direction and position. In this case, it was given by the Appleton-Hartree formula. She then defined a ray refractive index,

$$\mu' = ck\cos\psi/\omega \cdot \tag{28}$$

The ray path was then found by applying Fermat's principle of least time. This requires that the ray follows the path that at the ray velocity requires the least time. This implies that the change of phase along the ray path is a minimum, so that

$$\delta \int \mu' ds = 0 \cdot \tag{29}$$

From this condition she obtained a set of ray equations, written in general tensor notation, with contravariant and covariant tensors represented by upper and lower suffices.

They were

$$\frac{dx_j}{dt} = g^{ij}\frac{\partial G}{\partial u^i}, \qquad (30)$$

$$\frac{du_j}{dt} = -g^{ij}\frac{\partial G}{\partial x_i} - g^{ij}g^{km}u^l\frac{\partial G}{\partial u^m}\left(\frac{\partial g_{li}}{\partial x_k} - \frac{\partial g_{kl}}{\partial x_i}\right).$$

These can be written in various coordinate systems. Haselgrove presented explicit expressions for Cartesian and polar coordinates for a magnetoionic medium.

3.3 Energy Propagation in Geometrical Optics

3.3.1 Group Velocity and Energy Flux

It is often stated that the group velocity is the velocity of energy propagation, although this is seldom shown explicitly in elementary texts. When dealing with the energy propagated by a wave that is a small perturbation on the background, and which is assumed to vary in space and time according to Equation (1), care is necessary in calculating the energy associated with the wave. The problem has been given a very full treatment by Gershman and Ginzburg [19]. That paper was in Russian. An English translation appeared in the book by Ginzburg [20]. They treated a general medium, including the effects of spatial dispersion. We simplify the treatment to neglect spatial dispersion, so that the dielectric tensor depends only on *w*, and is independent of **k**.

Poynting's theorem for an electromagnetic wave in a dispersive anisotropic medium may be written as

$$-\frac{\partial}{\partial t}\left\{\frac{1}{2}\mathbf{D}\bullet\mathbf{E} + \frac{1}{2}\mathbf{B}\bullet\mathbf{E}\right\} = \nabla\bullet\{\mathbf{E}\times\mathbf{H}\}. \qquad (31)$$

Here,

$$U \equiv \frac{1}{2}\mathbf{D}\bullet\mathbf{E} + \frac{1}{2}\mathbf{B}\bullet\mathbf{E} \qquad (32)$$

is interpreted as the energy density associated with the wave, and

$$\mathbf{\Pi} \equiv \mathbf{E}\times\mathbf{H} \qquad (33)$$

is interpreted as its energy flux.

The representation of sinusoidal wave behavior by an exponential, with the understanding that the real part of complex quantities represents the physical behavior of wave variables, only works for linear combinations of the wave variables. The expressions for the energy variables involve nonlinear products of the field variables, **E, B, D,** and **H**. In order to evaluate the expressions for the energy flux and density, the real parts of these variables must first be taken. If this is done and the result averaged over one cycle of the wave, the average energy density and flux are

$$\langle \mathbf{\Pi} \rangle = \tfrac{1}{2}\Re\left\{\mathbf{E}\times\mathbf{H}^*\right\}, \qquad (34)$$

$$\langle U \rangle = \tfrac{1}{2}\Re\left\{\mathbf{D}\bullet\mathbf{E}^* + \mathbf{B}\bullet\mathbf{H}^*\right\}.$$

(See, for example, [21, 22].)

Now Maxwell's curl equations for the field variables, in the absence of conduction currents, are

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}, \qquad (35)$$

$$\nabla\times\mathbf{H} = \frac{\partial\mathbf{D}}{\partial t}.$$

For plane harmonic waves, we can replace ∇ by $i\mathbf{k}$, and $\partial/\partial t$ by $-i\omega$, obtaining

$$\mathbf{k}\times\mathbf{E} = \omega\mathbf{B}, \qquad (36)$$

$$\mathbf{k}\times\mathbf{H} = -\omega\mathbf{D}. \qquad (37)$$

If we now take the scalar product of $\mathbf{H}^*$ with Equation (36) and $\mathbf{E}^*$ with Equation (37), we get

$$(\mathbf{k}\times\mathbf{E})\bullet\mathbf{H}^* \equiv \mathbf{k}\bullet\left(\mathbf{E}\times\mathbf{H}^*\right) = \omega\mathbf{B}\bullet\mathbf{H}^*,$$

$$\mathbf{E}^*\bullet(\mathbf{k}\times\mathbf{H})^* \equiv -\mathbf{k}\bullet\left(\mathbf{E}^*\times\mathbf{H}\right) = -\omega\mathbf{D}\bullet\mathbf{E}^*.$$

Now, subtract the second from the first:

$$\mathbf{k}\bullet\left\{\mathbf{E}\times\mathbf{H}^* + \mathbf{E}^*\times\mathbf{H}\right\} = \omega\left\{\mathbf{B}\bullet\mathbf{H}^* + \mathbf{D}\bullet\mathbf{E}^*\right\}. \qquad (38)$$

The frequency ω is related to **k** through the dispersion relation. For a propagated wave with no losses, **k** is real. We limit our discussion to the case where there is no spatial dispersion, so that the dielectric tensor depends on $\omega(\mathbf{k})$, but not explicitly on **k**. This means that we assume that the plasma is cold. In the absence of losses, the permeability tensor relating **D** and **E** is Hermitian, as in Equation (4).

Equation (38) can be added to its complex conjugate, and the result divided by two, to get

$$\mathbf{k}\bullet\left\{\mathbf{E}\times\mathbf{H}^{*}+\mathbf{E}^{*}\times\mathbf{H}\right\}$$

$$=\omega\left\{\frac{1}{2}\left(\mathbf{B}\bullet\mathbf{H}^{*}+\mathbf{B}^{*}\bullet\mathbf{H}\right)+\frac{1}{2}\left(\mathbf{D}\bullet\mathbf{E}^{*}+\mathbf{D}^{*}\bullet\mathbf{E}\right)\right\} \quad (39)$$

The time-averaged flux vector given by Equation (34) can be retrieved from this by taking the gradient in k space. However, in doing this care must be taken because the field components are the amplitudes in the Fourier spectrum, and are themselves functions of **k**. In addition, if we use the constitutive relation of Equation (3) to express **D** in terms of **E**, the dielectric tensor is a function of w and, hence, of **k**. The result of the operation is

$$\left\{\mathbf{E}\times\mathbf{H}^{*}+\mathbf{E}^{*}\times\mathbf{H}\right\}_{i}$$

$$=\frac{\partial\omega}{\partial k_i}\left\{\tfrac{1}{2}\frac{\partial\left(\omega\varepsilon_{jk}\right)}{\partial\omega}E_kE_j^{*}+\tfrac{1}{2}\frac{\partial\left(\omega\varepsilon_{jk}\right)}{\partial\omega}E_k^{*}E_j+\frac{B^2}{\mu_0}\right\}$$

$$+\frac{\partial E_k}{\partial k_i}\left\{\mathbf{k}\times\mathbf{H}^{*}+\omega\mathbf{D}^{*}\right\}_i+\frac{\partial E_k^{*}}{\partial k_i}\left\{\mathbf{k}\times\mathbf{H}+\omega\mathbf{D}\right\}_i$$

$$+\frac{\partial H_k}{\partial k_i}\left\{-\mathbf{k}\times\mathbf{E}^{*}+\omega\mathbf{B}^{*}\right\}_i+\frac{\partial H_k^{*}}{\partial k_i}\left\{-\mathbf{k}\times\mathbf{E}+\omega\mathbf{B}\right\}_i \quad (40)$$

This is written for brevity in a hybrid notation. The subscripted braces represent the i components of the vector expressions contained in them. Repeated subscripts imply summation. From Equations (36) and (37) and their complex conjugates, we see that the quantities multiplying derivatives of the field components are zero. Although for simplicity we have assumed that the dielectric tensor depends on **k** only through its dependence on ω, the same result is obtained even for media with spatial dispersion in which there is an explicit dependence on **k** [20]. The equation therefore becomes

$$\mathbf{E}\times\mathbf{H}^{*}+\mathbf{E}^{*}\times\mathbf{H}=\nabla_k\omega\left\{\tfrac{1}{2}\tilde{\mathbf{D}}\bullet\mathbf{E}^{*}+\tfrac{1}{2}\tilde{\mathbf{D}}^{*}\bullet\mathbf{E}+\frac{B^2}{\mu_0}\right\} \quad (41)$$

where $\tilde{\mathbf{D}}$ is a modified form of the electric displacement, given, in suffix notation, by

$$\tilde{D}_i=\frac{\partial\left(\omega\varepsilon_{ij}\right)}{\partial\omega}E_j=\varepsilon_{ij}E_j+\omega\frac{\partial\varepsilon_{ij}}{\partial\omega}E_j=D_i+\omega\frac{\partial\varepsilon_{ij}}{\partial\omega}E_j \quad (42)$$

Equation (41) can be divided by four to get

$$\left\langle\mathbf{\Pi}\right\rangle=\mathbf{V}_G\left\langle\tilde{U}\right\rangle, \quad (43)$$

where $\left\langle\mathbf{\Pi}\right\rangle$ is the time-averaged Poynting vector given by Equation (34), and $\left\langle\tilde{U}\right\rangle$ is a modified time-averaged energy density given by

$$\left\langle\tilde{U}\right\rangle=\tfrac{1}{2}\Re\left\{\tilde{\mathbf{D}}\bullet\mathbf{E}^{*}\right\}. \quad (44)$$

This equation states that the time-averaged Poynting vector represents the flux of a quantity $\left\langle\tilde{U}\right\rangle$ that is transported at the group velocity. The additional term in the expression for the modified electric displacement arises because we are considering a wave packet, and the dielectric tensor must be appropriately averaged over the range of wavelengths and directions in the wave packet.

Provided that we take these effects into account, we see that the ray represents the path along which energy is propagated, and that the energy in a wave packet, given by Equation (44), is propagated at the group velocity.

3.4 Intensity Variation Along Rays

We have seen that if the medium is sufficiently slowly varying so that the approximations of Geometrical Optics are valid, then the direction of energy propagation is the direction of the ray. We define a ray tube as a region of space bounded by a set of rays. This means that for a ray tube with varying cross section ΔS,

$$\int_{\Delta S}\mathbf{\Pi}.d\mathbf{S}=\text{constant}, \quad (45)$$

i.e., energy is conserved along the ray tube. Since the energy flux is proportional to the square of the intensity, this means that a calculation of the variation of the elementary cross section $\hat{\mathbf{n}}\bullet d\mathbf{S}$ along the ray gives the inverse of the variation of the intensity along the ray. Of course, one could calculate the cross section by computing three ray paths defining the corners of a triangular ray tube, and then computing the area of the triangle directly from the ray coordinates at various distances along the ray tube. This is inherently inaccurate. One requires a method that allows one to deduce the cross section directly while integrating along the path of a single ray. One such method was developed by Harvey (in an unpublished PhD thesis at Cambridge University in 1968), using the Gaussian curvature of the refractive-index surface to find the divergence of the ray. A similar method of calculating the cross section, by integrating a further set of equations along the path of a single ray, was developed by Buckley [23]. Buckley's method involves finding a set of additional first-order differential equations giving the rates of change of **r** and **k** at a fixed time with respect to the initial wave vector, $\mathbf{k}_0$, at the source. These additional equations are written as two simultaneous equations for second-rank three-dimensional Cartesian tensors. There are therefore 18 additional equations to be integrated, although there is some redundancy. For a discussion, see the work by Budden [24]. In practice, this method has seldom been used, and it is to be hoped that authors will take note of it and assess its usefulness.

3.5 Attenuation and Amplification

So far, we have assumed that the medium is loss free. Changes in signal intensity occur for two reasons. One is focusing or defocusing, as discussed Section 3.4. The other is because the wave loses energy because of interaction with the background medium. In the ionosphere at HF, the major loss mechanism is because of collisions between the electrons and background neutral particles, and early work was influenced by this mechanism for losses (see, for example, [25]).

In such a mechanism, the losses can be calculated from the collision frequency, which must be provided as a function of position as part of the model. In practical cases, the losses are small; if they were not, the signal would be absorbed in a few wavelengths, and the ray tracing would be futile. In this case, the technique is to assume that the ray path, to zero order, is unaffected by the collisions. The wave vector, **k**, has a small imaginary part, and we can write its magnitude as $k + i\chi$. Then, if $d\mathbf{s}$ is an element of the ray path, it makes an angle ψ with the wave normal, and field components vary as

$$\exp\left\{i\left(k+i\chi\right)\cos\psi\, ds\right\}$$

$$= \exp\left\{-\chi\cos\psi\, ds\right\}\exp\left\{ik\cos\psi\, ds\right\}. \quad (46)$$

If the ray-tracing equations are expressed in the form of Equations (21) and (22), then

$$\frac{ds}{dt} = V_R = \frac{V_P}{\cos\psi} = \frac{\omega}{k\cos\psi}. \quad (47)$$

The losses thus cause the amplitude to vary along the path as

$$A = A_0 \exp\left\{-\left(\omega\chi/k\right)dt\right\}, \quad (48)$$

so that

$$\frac{d\left(\ln A\right)}{dt} = -\frac{\omega\chi}{k}. \quad (49)$$

This equation can be integrated simultaneously with the ray-tracing equations to find the losses due to collisions.

In the magnetosphere, the density of neutral particles is always negligible. Other forms of collisions, such as binary Coulomb collisions or effective collisions due to distant Coulomb interactions, have effective collision times that are extremely long, and such interactions can always be neglected. The exchange of energy between wave and environment can still take place through resonant wave-particle interactions. Such interactions take place when the wave speed is small, so that they are comparable with particle speeds. They include Landau damping, in which particle and wave speeds are the same, and there is a longitudinal component of electric field to accelerate the particles. Particles moving along the magnetic-field direction at a slightly greater speed than the wave lose energy to the wave; particles moving at a slightly smaller speed gain energy from it. Since in a normal distribution there are more particles traveling more slowly, there is a net energy transfer from wave to particles. When the particle distribution is not an equilibrium distribution it is possible that net energy flows from particle to wave, in which case there is amplification. The other interaction of importance is Doppler-shifted cyclotron resonance, where, in the guiding-center frame of the particles, the Doppler-shifted wave frequency matches the cyclotron frequency of one of the particle species – either electrons or ions.

Ray tracing can tell us nothing about these interactions. What it can do is to tell us where the wave has a location and phase velocity that allows the interactions to take place. The nature of the damping or amplification then needs the application of the appropriate kinetic theory.

4. Recent Applications of the Ray-Tracing Equations to Propagation Problems in the Magnetospheres of Earth and Other Planets

Ray tracing has become an indispensable tool in the study of magnetospheric waves. Many hundreds of magnetospheric papers have been published having results that are based on ray-tracing calculations since the technique was first developed. In the past three years, the author has identified 85 such papers, and there are probably more. In 2007 alone, at the time of writing, 28 such papers have already appeared. It is not the intention of this review to provide an exhaustive list of these publications. Instead, a limited number of papers that illustrate the application of

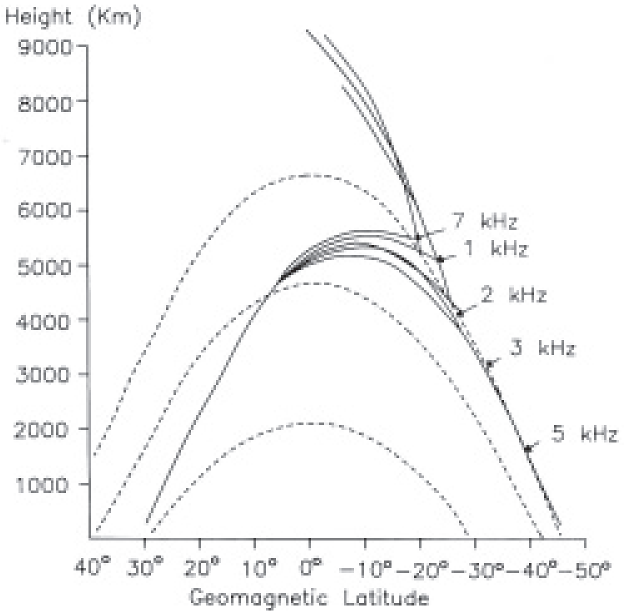

Figure 5. Ray paths at frequencies below 5 kHz when the effect of positive ions is included, showing magnetospheric reflection. The dashed lines represent the magnetic field. Note that these are not scale illustrations, since the vertical axis shows height in kilometers, and the horizontal axis shows geomagnetic latitude [P. D. Terry, private communication].

ray tracing in a variety of different environments have been selected for brief discussion. The choice is a personal one, and it is recognized that many excellent works have been omitted. In each case a brief early history of the phenomenon is given, and current work is then reviewed.

4.1 Whistlers and Chorus

Whistlers originate in lightning flashes, as was first explained by Storey [26]. Because of the nature of the refractive-index surface, they are propagated along the magnetic field and the frequency components of the original impulse are dispersed with different delays, producing a descending whistling sound when played through an audio amplifier. Early ray-tracing studies [27] showed that Storey's mechanism needed some modification, as the ray paths of whistlers were not exactly field-aligned. In a dipole-field model, while the ray remained approximately aligned with the field, the wave normal made larger and larger angles with the magnetic field until the resonance angle was reached. Whistlers observed on the ground had to be guided by field-aligned ducts that occur naturally in the plasma [28]. When the effect of positive ions is included, the refractive-index surface shown in Figure 4 is closed, rather than having a resonance cone. This occurs in the neighborhood of the lower hybrid resonance. As a consequence, the whistler is reflected back into the magnetosphere as shown in Figure 5, and we have an un-ducted magnetospherically reflected, or MR, whistler [29].

Another phenomenon related to this was also discussed by Storey. This was a complicated series of rising and falling tones, which, when played through an audio amplifier, resembled the chirruping sound of birds – their dawn chorus – as heard in the early morning. Storey therefore named the phenomenon "dawn chorus." This name led to much confusion, as workers outside the United Kingdom, who were not familiar with the term relating to birdsong, were quick to point out that the VLF phenomenon was not restricted to dawn. Ultimately, the word "dawn" was dropped, and the phenomenon is now known as chorus. The discrete signals arise from interaction between energetic particles and whistler waves as a result of Doppler-shifted cyclotron resonance. After generation, the waves are propagated in the whistler mode, and may reach parts of the magnetosphere remote from the source.

The four CLUSTER spacecraft form one of the most powerful facilities for elucidating the temporal and spatial behavior of magnetospheric processes. Platino et al. used ray-tracing techniques to study the propagation of whistlers originating in atmospheric lightning flashes and propagated to the spacecraft [30]. Outside the plasmapause in the low-density region, they found that whistlers were only observed in the presence of large-scale field-aligned irregularities, so they can be ducted. Using all CLUSTER passes in 2001 and 2002, a search for whistlers showed that their dispersion can only be explained if the rays have followed a field-aligned path as a result of ducting.

Other studies of whistler propagation relate to chorus. The CLUSTER spacecraft have provided data that have stimulated the production of much recent work in this field. The spectrum analyzer on board allows the computation of the Poynting vector of whistler-mode chorus. Parrot et al. [31] found that the most intense chorus waves are propagated away from the source region at the equator. However, lower intensity waves were observed as propagated towards the source region. A ray-tracing study showed that these waves are magnetospherically reflected near the lower hybrid resonance, and return to the equator at a different location and with lower intensity. At this stage, they were beginning to lose coherence, but had small wave-normal angles favorable for amplification. It was suggested that they could be a source of hiss. Chum et al. [32] studied the propagation of chorus from the source. They used ray tracing to determine the effect of the angular distribution of the initial wave-normal direction. By assuming an initial size for the source region they studied the range of frequencies arriving at a particular destination, so explaining the observed bandwidth of chorus emissions. Chum and Santolik [33] continued this topic to study how such waves reach the ground, while Chum et al. [34] modeled the signals reaching the different CLUSTER spacecraft using ray tracing to follow the signal from an assumed source. They could reproduce signals similar to those observed. Breneman et al. [35] used a similar ray-tracing approach to study specific events and locate the source region. In one case, they found a common source region for the group of CLUSTER spacecraft; in a second case, they found no common source.

Bortnik et al. [36] studied the topic of interaction of particles with whistler-mode chorus. Ray tracing showed that waves generated with wave normals near the Gendrin angle are propagated to high L values with little or no Landau damping, and may energize 1 MeV electrons. Further work on these lines [37] went into detailed modeling of waves observed by the CRRES satellite. The results of this modeling were consistent with observations. The chorus is modified by Landau interaction with suprathermal electrons, which control the chorus distribution. During the recovery phase of substorms, the chorus contributes to acceleration and loss of relativistic electrons, so that the suprathermal electrons, mediated by the chorus, have a significant effect on radiation-belt dynamics.

4.2 Ion-Cyclotron Waves

Wave-particle interactions are important in the plasma dynamics of the ring current. Recently, elaborate models of the ring current have been developed that include such interactions. Khazanov et al. [38] produced a self-consistent model of the ring current that interacts with and is affected by ion cyclotron waves. Their ray-tracing equations in a dipole model used the dispersion relation for a cold multi-ion plasma. The waves are important mediators of energy transfer. The tool of ray tracing allowed them to follow the paths of ion-cyclotron waves, to show how the waves are organized in space, and to find the locations where various wave-particle interactions can take place. The model allowed them to model the waves during an observed magnetic storm. They showed their importance for downward heat transport through energy transfer to thermal electrons, and for excitation of stable auroral red arcs.

4.3 Active Experiments

Ionospheric-heating experiments have been carried out over many years. Such experiments have been carried out at the location of EISCAT in Norway; at the HAARP facility at Gakona, Alaska; and at the SURA facility at Nizhny Novgorod, Russia. In such experiments, high-power HF signals are used to heat the lower ionosphere. One intriguing result of such experiments is that modulated HF heating can cause variations in the conductivity and, hence, modulate the electrojets, which can act as transmitting antennae for VLF, ELF, and ULF waves. Another topic of interest is the HF pumping of the ionospheric plasma at harmonics of the gyrofrequency, energizing the ionospheric plasma to produce optical emissions in the form of airglow. In both these studies, ray tracing has been used as a tool.

Platino et al. [39] studied the propagation of the waves generated by the HAARP through electrojet modulation to the CLUSTER spacecraft. They used ray tracing to determine the location of the injection of the ELF/VLF waves into the magnetosphere. They were also able to provide a possible explanation of the spectral signature.

The ray tracing used in the context of the HF pumping of the ionosphere is very different. Here, the interest is in finding the path of the HF signal in an ionosphere that has been depleted by the heating process. Grach et al. [40], using the SURAS facility, noted that for vertical pumping, the airglow patch moved increasingly northward. For very bright emissions, the patch developed at the northward edge of the pump beam and expanded southward. For a pump beam inclined southward by 12°, the patch was displaced southward by an amount larger than predicted by ray tracing. Kosch et al. [41], using HAARP, used ray tracing through the depletion region, which forms a concave mirror. They were able to reproduce the morphology of the observed airglow.

4.4 Jupiter

Flybys of Jupiter by Voyager and Galileo showed "lanes" in which radio emissions were attenuated. Menietti et al. [42] used Galileo/Cassini observations at many frequencies and locations to place constraints on the parameters of a model magnetosphere. Ray tracing in the model has shown that refraction of the wave can produce the attenuation lanes. The results were also used to restrict the possible locations of sources of hectometric radiation.

5. Discussion and Conclusions

Versions of the ray-tracing technique in an anisotropic medium first introduced by Jennifer Haselgrove have been in continuous use during the past fifty years. Interestingly, the rate at which the technique is used is steadily increasing. In the early years, the demands on the capacity of the computers of the day made it a difficult and tedious process. As computing power has increased, extensive ray-tracing calculations have become feasible, and it is possible to carry out extensive calculations rapidly and efficiently.

The ray-tracing technique was first introduced to the ionospheric community in 1954 at the Physical Society Conference on the Ionosphere. The applications were seen to be to radio wave propagation in the ionosphere. Owen Storey's paper on whistlers had only been published the previous year, and suggested the possibility of a higher density of plasma above the ionosphere than had previously been assumed. The scientific community stood on the threshold of space, with no concept of the complexity of geospace. The early years of the space race, with the discovery of the radiation belts, the mapping of the external geomagnetic field, the observation of plasma populations, and all the advances in scientific cooperation initiated by the International Geophysical Year, were yet to come. The concept of the magnetosphere only became firm in the early nineteen sixties. It is therefore serendipitous that ray tracing as introduced by Haselgrove has become so important in magnetospheric work, as is shown by the examples presented in this review.

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World-Wide Lightning Location Using VLF Propagation in the Earth-Ionosphere Waveguide

Richard L. Dowden et al.

Abstract

Worldwide lightning location (WWLL) using only 30 lightning sensors has been successfully achieved by using only VLF propagation in the Earth-ionosphere waveguide (EIWG). Ground propagation or mixed "sky" and ground propagation is avoided by requiring evidence of Earth-ionosphere waveguide dispersion. A further requirement is that the lightning strike must be inside the perimeter defined by the lightning sensor sites detecting the stroke. Under these conditions, the time and the location of the stroke can be determined, along with the rms errors. Lightning strokes with errors exceeding 30 μs or 10 km are rejected.

To assist with identifying impulses from the same lightning stroke, the lightning sensor threshold is automatically adjusted to allow an average detection rate of three per second. This largely limits detection to the strongest 4% of all lightning strokes, of which about 40% meet the accuracy requirements for time and location.

1. Introduction

This lightning-location network was conceived by Low Frequency Electromagnetic Research (LFEM), set up by one of us in Dunedin, New Zealand, on retirement from the University of Otago where the first lightning sensor was sited. The intention was to locate the lightning strokes that trigger "red sprites," which were being detected by LFEM both optically and by VLF perturbations at two sites near Darwin, Australia. At that time (1995-2001), the only available lightning location network (Kattron, using time-of-arrival) served southeast Australia, where most of the population resides. Initially, LFEM used VLF MDF (magnetic direction finding) sensors at the two Darwin sites, together with a VLF time-of-arrival (TOA) sensor at the Dunedin site. This was of limited success, even with the later addition of VLF time-of-arrival at Perth, Australia.

It was only when three more sensors were set up in August 2001, at Osaka, Japan; Singapore; and Brisbane that there were a sufficient number of sensor sites for lightning

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location by VLF time-of-arrival only (no magnetic direction finding). While the geographical extent of this network (70º in longitude, 80º in latitude) was far more than needed for sprites seen from Darwin, it resulted in LFEM being invited as an Industry Partner by the Australian Research Council to develop lightning location over sparsely populated areas in the northern half of Australia. This made the Worldwide Lightning Location Network (WWLLN) possible.

Gradually, the network was extended via contacts long known through international scientific conferences and ex-graduate students now spread around the world. By the beginning of 2003, the lightning location network (LLN) had become worldwide (WW). Currently, there are 30 WWLLN lightning receiving sites distributed around the world in longitude, and from the Antarctic to the Arctic in latitude.

2. Propagation

The use of the middle part of the VLF band (6 to 22 kHz out of 3 to 30 kHz for the full VLF band) is ideal for very-long-range lightning location. Propagation over distances of about 10,000 km is common, but since the attenuation in this band is around 1 or 2 dB per 1000 km (depending on propagation direction and time of day), the attenuation for propagation ’round the world (RTW), or even half-way around the world, is prohibitive. In any case, if a sferic arrived at a lightning sensor from a lightning stroke 10,000 km distant, but after traveling three-quarters of the way around the world instead of one-quarter, the time of arrival would be so wrong so that the location would simply be rejected. At higher frequencies (LF, MF, and HF), propagation is far more limited in range and unreliable for location by timing, unless restricted to groundwave propagation.

The WWLLN exclusively uses propagation in the Earth-ionosphere waveguide (EIWG). It has been found that mixing “skywave” (Earth-ionosphere waveguide) propagation with “groundwave” (line-of-sight) propagation leads to significant LL (lightning location) errors. This has long been known in the case of short-range (a few 100 km) networks using time-of-arrival and/or magnetic direction finding. These avoid skywave propagation by using only the first few microseconds of the lightning impulse [1], which is equivalent to limiting the low frequencies to a few hundred kHz. Earth-ionosphere waveguide propagation shows the characteristic phase as a function of frequency shape of waveguide dispersion. Superposition of groundwave signals changes this shape to give a bad correlation with the theoretical shape, as well as to give it the opposite trend. Impulses that show this opposite trend are not included as genuine lightning impulses (“sferics”).

VLF propagation in the Earth-ionosphere waveguide is largely restricted to the quasi-TE and quasi-TM modes. The dispersionless TEM mode is possible, but highly attenuated at VLF. The “quasi” term arises because – unlike a waveguide formed by two infinite, conducting, parallel planes – the upper bound (the ionosphere) is not sharply defined, is partly a conductor and partly a dielectric, and both properties depend on frequency. The lower bound, particularly if it is a smooth ocean, is a much better approximation to a horizontal plane conductor. The boundary conditions at this conductor require that the horizontal component of the electric field be zero, so only the TM (transverse magnetic) modes, the electric field of which is vertical at the smooth ocean surface, provide the VLF signal we need.

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A monochromatic wave propagating in the Earth-ionosphere waveguide in both the TM_1 and TM_2 modes can, at some *point* along the path, have zero amplitude if the two modes have equal amplitude and opposite phase at that *point*. The 3 dB bandwidth of the spherics as seen by the lightning receivers is over 3:1 (6 kHz to 22 kHz). This means that a sferic propagating in the Earth-ionosphere waveguide in both the TM_1 and TM_2 modes can, at some *frequency* along the path, have zero amplitude if the two modes have equal amplitude and opposite phase at that *frequency*. This has been observed [3], but it is rarely significant, and it is rejected in any case if it affects the dispersion curve.

The typical lightning return-stroke current decays to half peak in about 40 µs [2]. The radiated pulse is dispersed into a wave train in the Earth-ionosphere waveguide. For 10 Mm propagation, the amplitude of this wave train rises from the noise floor to maximum in about 200 µs, and then decays to half maximum in about 400 µs [3]. There thus is no sharp pulse from which to measure the time of arrival. Instead, we do the following. The VLF signal, comprising the sferics, VLF communication transmissions, power-line harmonics, etc., is continuously sampled at 48 kS/s – as is the GPS PPS (pulse per second) for precision timing – and stored in a buffer. When the difference between two consecutive samples exceeds a predetermined threshold, 64 samples are grabbed from the buffer: 16 samples (333 µs) from before the grab and 48 samples (1000 µs) after, which contains the whole waveform. From the rate-of-change of wave phase with respect to frequency, we get the time of group arrival (TOGA) to within one microsecond or so [3].

The geometric mean of the band limits (6 kHz and 22 kHz) over which we make the measurement of the time of group arrival is about 12 kHz. At this frequency, the Earth-ionosphere waveguide group velocity during the day is equal to that at night [6], at about 0.9922*c* [0.9922 times the speed of light in vacuum). This frequency is near the maximum spectral density of lightning radiation [7, 8], which extends from a few hertz to optical frequencies. The wavelength of this maximum is about 30 km.

3. VLF Antennas

Most of the antennas discussed in this journal are for millimeter wavelengths, so engineers designing these need a drastic rethink when the wavelength increases some seven-and-one-half orders of magnitude. VLF antennas used for lightning detection have dimensions of less than 3 m, and so are less than a ten-thousandth of a wavelength. Being so small, loop antennas are sensitive only to magnetic fields, are impervious to electric fields, and have very low output impedance. VLF magnetic fields are shielded (cancelled) by induced currents, so adequate shielding from magnetic fields produced by electric-power reticulation on university and institute campuses requiring extremely good (and so, very thick) conductors is not feasible. At the other extreme are vertical whip antennas of about 1 m long, "counterpoised" by a longer metal pole, hand rails, etc. Such antennas are sensitive only to electric fields, are impervious to magnetic fields, and have very high output impedance (almost purely capacitive at around 15 pF; the impedance at 10 kHz is ~1MΩ). VLF electric fields are shielded (cancelled) by induced charge, so quite poor conductors can provide adequate shielding from electric fields produced by electric-power reticulation on university and institute campuses. Having the power lines underground or behind the walls and roofs of ferro-concrete buildings may thus be all that is needed. What is to be avoided is the unintentional shielding of the VLF electric fields of the sferics: the lightning impulses needed for lightning location.

For VLF (λ~30km) sources within about 5 km ($\lambda/2\pi$) of the VLF antenna, the induction field dominates, so for the dimensions of campuses and city blocks, VLF can be approximated by zero frequency. The VLF-wave electric field can thus be approximated by an electrostatic field. As pointed out in Section 2, the electric field at a plane horizontal ground is vertical. An ideal site for the VLF antenna would therefore be on a horizontal conducting plane with horizontal dimensions of a few wavelengths. Obviously, such a site is certainly not to be found on a university or institute campus. We have to compromise, because we need electric power for the VLF receivers and processing computers, we need

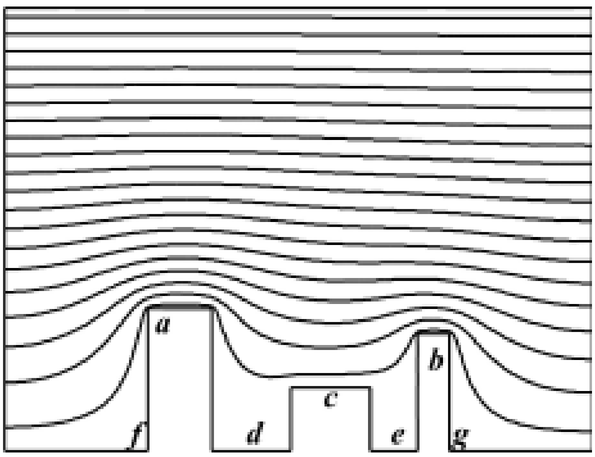

Figure 1. Electric equipotential surfaces calculated from Laplace's equation ($\nabla^2 = 0$) for the boundary conditions: the outline of the three buildings and the ground (an infinite horizontal plane) on which they stand was at zero potential, and the top border of this picture was an infinite horizontal plane at 100% potential. All were perfect conductors. The equipotential surface immediately above the buildings and ground was at 2.5%. Thereafter, consecutive equipotential surfaces increased in 5% steps, except for the last step (2.5%). Thus, beginning at the bottom, the percent potentials were: 0, 2.5, 7.5, 12.5, … 92.5, 97.5, 100. The electric field was everywhere normal to the equipotential surfaces. The letters a, b, c, … g indicate good and bad locations for the very small VLF antenna, as discussed in the text.

the Internet for continuous transmission of the times of group arrival, and, in particular, the VLF receiving sites must be convenient to the authors of this paper, who make the WWLLN work. This means that the VLF antennas must be suitably sited on the campuses of their universities or institutes. These campuses, being different from the ideal horizontal conducting plane, greatly affect the VLF electric field in magnitude and direction. This can be used to advantage: suitable sited on campus, the signal from the VLF antenna can be greatly enhanced; badly sited, the signal from the VLF antenna can be reduced to the noise level.

Figure 1 shows the outline of three buildings on campus, well-separated from other buildings (buildings, masts, trees, etc., not shown are "infinitely" remote). All three buildings have flat roofs, free of antennas and dishes, and even free of parapets. At altitudes of more than twice the height of the tallest building, the equipotential surfaces are nearly plane, nearly horizontal, and nearly evenly spaced. The electric field is thus nearly uniform, vertical, and nearly independent of altitude. The electric field is everywhere normal to the equipotential surfaces, and equal in magnitude to the potential gradient: high where consecutive equipotential surfaces are close together, and low where they are far apart.

From Figure 1, we see that the highest electric fields, and so the best VLF antenna sites, are at (actually above) *a* or *b*, the outside edges of the roofs of tall buildings. The electric field, being normal to the equipotential surfaces, is tilted out and away from vertical, so the VLF antenna can also be tilted with advantage. This is particularly important if the roof of the building has a forest of antennas and dishes, as is often the case on buildings for geophysicists and electrical engineers. The roof of the middle building (above *c*) is partly shielded by the higher buildings on either side. Comparing the distance of the equipotential surface above this roof at *c* with the distance of the same equipotential surface from *a* or *b* implies that a short (1 m) VLF antenna site at *c* would receive only a tenth of the field of one sited at *a* or *b*.

Siting the VLF antenna on the ground between buildings at *d* or *e*, or close to an isolated tall building at *f* or *g*, can result in no usable signal at all.

4. Transmitter (Lightning-Stroke) Identification

In many respects – with one major difference – the Omega global navigation system [4] was similar to the WWLLN. Although Omega appeared to use phase differences at different frequencies, this was equivalent to using the rate of change of phase with respect to frequency to get the group travel time from each transmitter to the receiver. Omega thus used and WWLLN thus uses the time of group arrival: Omega to get the receiver position, knowing the exact location of the VLF transmitters, and WWLLN to get the transmitter (lightning-stroke) position, knowing the exact positions of the WWLLN receivers.

The major difference between Omega and WWLLN is that the eight Omega transmitters identified themselves by transmitting a unique frequency. In contrast, a lightning impulse (sferic) appears much the same as any other. Locating lightning-stroke X requires the times of group arrival at a minimum of four receivers, each of which are receiving about 100 sferics per second from distances in all directions of up to about 13 Mm.

Of the four (or more) WWLLN sites that "see" lightning-stroke X, the nearest to the stroke may be only 1000 km from it, while the furthest may be over 13,000 km from it. The spread in times of group arrival would thus typically be about 30 ms. Superimposed on this set of times of group arrival are the times of group arrival from strokes other than stroke X, which are arriving at these WWLLN sites at a random rate of about 100 per second, and so with a typical (but very variable) separation of around 10 ms. This means that several sferics (and time-of-group-arrival values) from other strokes will arrive at each of the WWLLN sites receiving sferics from stroke X during the 30 ms it takes to get the sferics from stroke X. All of these times of group arrival are sent to the central processing computer (CPC) for analysis. Each time of group arrival carries a label to say which WWLLN station received it, *but no label to say which lightning stroke produced it.*

To resolve this, consider the US nationwide network of ARSI time-of-arrival sensors (see [5, Section 17.5, p. 565]), which used about 60 time-of-arrival receivers, a few hundred km apart, and which used only a few microseconds of the lightning pulse to ensure that the lightning pulse arrived without a skywave component. This meant that a stroke to be detected occurred within a few hundred km of a least four lightning sensors. The times of arrival (TOAs) could all be the same at each of the four stations, but were more likely spread over, say, 1 ms, corresponding to the furthest of the four lightning sensors being 300 km further from the lightning stroke than the nearest. The National Lightning Detection Network central processing computer gets a short (~1ms) clump of times of arrival from the designated four lightning sensors. Did this result in overlapping clumps?

To answer that last question, consider the US state, Florida, which gets the most lightning. An estimate [5] is that a given square meter would be struck by lightning once in 10^5 years, or about once in 3×10^{12} seconds. If we expand the area to 10^{12} m^2 (a circular area of radius ~600 km that should enclose four or more sensors), we would expect one stoke per three seconds. However, many of these would be part of a flash of strokes separated by only a few tens of ms. Even so, the likelihood of overlapping clumps, each only 1 ms long, is very small.

Clearly, a requirement for WWLLN was to somehow cause the times of group arrival from individual lightning strokes to form non-overlapping clumps. A second requirement was to detect and suppress bad locations caused by including one or more sferics (and corresponding times of group arrival) from lightning strokes other than the stroke the location of which is sought. A third was to detect and remove "rogue" times of group arrival from the location algorithm. This last requirement is conditional on the number of times of group arrival exceeding the minimum number allowed. We now discuss how we incorporated these requirements.

At no time was the sensitivity of the WWLLN lightning sensors set high enough to detect all of the globe's lightning strokes. However, during the first year, when we had only six receiver sites, a thunderstorm over one of the sites caused hundreds of sample triggers per second and overloaded the whole network, such as it was at that time. These triggers were caused by electric-field pulses due to the thunderstorm, although not by visible lightning. As a result, we added an automatic threshold control (ATC) to each lightning sensor to limit the average (over a few minutes) number of times of group arrival transmitted to the central processing computer. This automatic threshold control number is currently set to three times of group arrival per second at each WWLLN site. This, in itself, reduces the overlap of clumps of "monostroke" times of group arrival (all from the same lightning stroke) to the extent that the clumps span less than 30 ms and are typically spaced 300 ms apart.

Limiting the detection rate limits capture (for analysis and lightning location) to strong strokes. Comparison of strokes located simultaneously by both WWLLN and an MF network that measures the stroke peak current revealed that strokes with peak currents less than 25 kA were rarely captured by the WWLLN. Those most commonly captured had peak currents of ~50 kA (stronger lightning strokes are more easily captured, but occur more rarely). Setting the automatic threshold control to higher values (more sferics per second) would capture weaker lightning, but would increase overlap and increase the cost to all the hosts of our WWLLN sites of transmitting the times of group arrival to the central processing computer.

5. Location-Error Estimate and Limiting

From a set of five or more times of group arrival assumed to result from a common lightning stroke, we locate the lightning stroke (find the latitude and longitude of the lightning stroke) using the "down-hill simplex" method (DHSM) [9]. As a zeroth approximation, we assume the lightning stoke occurred at the WWLLN site (call it X_0) that received it first (has the earliest time of group arrival). All the other WWLLN sites that detected the same lightning strike have later times of group arrival. We now calculate what those times of group arrival would have been had the lightning stroke happened at X_0. The earliest observed time of group arrival is that observed at X_0, so that that time of group arrival is the reference for the other calculated times of group arrival that differ from those observed. From the set of differences, or "errors," the down-hill simplex method gives a direction to move the zeroth approximation (X_0) "down hill" to a better approximation (X_1). For the lightning stroke at X_1, we calculate the times of group arrival, compare them to the observed times of group arrival, etc., find X_2, and so on for many further iterations, until the variance of the differences is not reduced by a further iteration. The final differences are called the "residuals:" what is left over and cannot be reduced by further iteration. The square root of the final variance is the "residual error." Lightning locations that have a residual error > 30 μs are suppressed (deleted from records). However, if the residual error exceeds 30 μs and if the number of WWLLN sites exceeds five, each providing a time of group arrival, we can examine the individual residuals, delete the time of group arrival corresponding to the worst residual, and run the down-hill simplex method process with the remaining times of group arrival. If the residual error still exceeds 30 μs and if the number of WWLLN sites still exceeds five, this can be repeated more times, until the residual error is reduced below 30 μs or the number of WWLLN sites (and so times of group arrival) is reduced to five, whichever comes first. This procedure works well if the worst residual is due to overlap (the result of a time of group arrival from a different lightning stroke) and is an outlier.

The residual error is not a direct indication of location error (inverse of location accuracy). That depends on the sensitivity of the residual error to displacement of the lighting-stroke position. To illustrate this, imagine the Earth to be one-dimensional, so that the Earth is just a single very long line. For lightning location, we need only two receivers, A and B, since any lightning must occur on the line. Now, a lightning stroke occurs at *X*, producing a sferic that arrives at WWLLN receiver A at time $TOGA_A$ and at B at $TOGA_B$. Our computer seeks to locate *X* using the down-hill simplex method discussed above. Since $TOGA_A$ is earlier than $TOGA_B$, the zeroth approximation, X_0, is at A, so the calculated time of group arrival for A is $TOGA_A$. In comparing the observed times of group arrival ($TOGA_A$ and $TOGA_B$) with the calculated times of group arrival, suppose $TOGA_B - TOGA_A$ is less than the group travel time from WWLLN receiver A to B. The down-hill simplex method "decides" that "down hill" is towards B, because moving this way initially increases the calculated time of group arrival at A and decreases the calculated time of group arrival at B, both of which reduce the error until eventually the residual is zero (even though the down-hill simplex method may overshoot a few times), and the lightning stroke is precisely located. This assumes that the observed times of group arrival have no measurement error. Suppose instead that the random measurement error in the difference $TOGA_B - TOGA_A$ is 10 μs. This might be attributed to a location error of x km along the line between A and B, which would change both $TOGA_B$ and $TOGA_A$ in opposite directions by $x/c = 5$ μs, where c is the speed of light, 0.3 km/μs, so x ~ 1.5 km.

Now, suppose another lightning stroke occurs, and again the zeroth approximation, X_0, is at A. In comparing the observed times of group arrival with the calculated times of group arrival, this time $TOGA_B - TOGA_A$ is *equal* to the group travel time from WWLLN receiver A to B. The down-hill simplex method "decides" that "down hill" is in the opposite direction, away from B and so also from A. Moving this way increases the calculated time of group arrival at A and increases the calculated time of group arrival at B by exactly the same amount, so the difference between the calculated times of group arrival remains equal to the difference between the observed times of group arrival, regardless of the position of X. In other words, the location of X when it is not between A and B is impossible. This effect can also occur on the real two-dimensional Earth's surface if we use only four WWLLN sites, three of which are closely grouped and the fourth is much further away. The outline of the set on the surface of the Earth is thus wedge-shaped, and then an enduring thunderstorm occurs *outside* the wedge near the point of the wedge. Lightning strokes produced by this storm are correctly located on the great circle along the axis of the wedge, but at different places along it. Such situations are reduced by requiring a minimum of five WWLLN sites receiving the sferics from the lightning stroke, which are less likely to form such wedge shapes. They are now eliminated by requiring that the lightning stroke is surrounded by receiving WWLLN sites.

The effect just described arises because in certain directions from the position of the lightning stroke, the geometric arrangement of the receiving WWLLN sites is such that the residual error varies very slowly so that its variation is masked by other small errors, resulting in false minima confusing the down-hill simplex method. We detect and eliminate these by measuring the variation of the residual error along four directions: N, NE, E, and SE, and the corresponding opposite four directions, by symmetry. For each of these directions, we deduce a positional error or uncertainty for that direction. If the error for any of the directions exceeds 10 km, we delete that location measurement from the records.

It was pointed out above that the residual error is not a direct indication of location error (inverse of location accuracy). However, it is in special cases. Consider four WWLLN sites arranged on the surface of the Earth in the form of a square, the diagonals of which are aligned N-S and E-W. The four WWLLN sites can then be designated N, E, S, and W. The dimensions of the square are not important, but we suppose them to be a few Mm to ensure that our approximations are valid. A lightning stoke exactly at the center of the square would be detected at all four WWLLN sites at the same instant, that is, the times of group arrival (TOGA) of the sferic would be the same. Now suppose a lightning stroke occurs 1.5 km North of the center of the square, and so is that much closer to N, the northernmost WWLLN site; that much further away from S; and a trivial distance (a meter or so) further away from both E and W. From the one-dimensional case discussed above, the time of group arrival at N (the northernmost WWLLN site) will be reduced 5 μs, while the time of group arrival at S (the southernmost WWLLN site) will be increased 5 μs. $TOGA(S) - TOGA(N)$ will thus increase by 10 μs. The opposite will result if a lightning stroke occurs 1.5 km south of the center of the square, except it will be the same trivial distance further away from both E and W. If many more lightning strokes occur along the N-S diagonal at random distances from the center of the square with a standard deviation (SD) of 1.5 km, the standard deviation of the time-of-group-arrival difference will be 10 μs. We have assumed that the displacement is from the exact center of the square, and exactly along the N-S diagonal. This assumption was to avoid any change to the times of group arrival at E and W. Since the diagonals are thousands of times longer than the displacements used here, we can expect the same results provided the random displacements are parallel to N-S but displacements normal to N-S are constant (and very small compared to the dimensions of the square).

Had we chosen the E-W diagonal instead of the N-S diagonal, then a random distribution of strokes along (or merely parallel to) the E-W diagonal with a standard deviation of 1.5 km would give a standard deviation of the time of group arrival E-W differences of 10 μs. We now replace the random displacements in only one direction (parallel to one diagonal) with independent random displacements in both directions, E-W (which we call x) and N-S (y), such that both displacement components, x and y, have a standard deviation of 1.5 km (giving a radial displacement standard deviation of $1.5\sqrt{2}$ km), so the standard deviation of the differences in times of group arrival at diagonally opposite WWLLN sites at the corners of the square are 10 μs.

Having found the effect on the times of group arrival of a normal distribution of lightning strokes about the center of the square, we reverse the process to find the effect of random measurement errors of the times of group arrival (all with the same standard deviation) on the lightning-stroke location error. Moving a lightning stroke towards a WWLLN site moves it away from one in the opposite direction because the WWLLN sites are fixed, so the times of group arrival are coupled. To estimate stroke-location errors from *independently* random time-of-group-arrival errors, to get a standard deviation of 10 μs in the time-of-group-arrival *differences* for times of group arrival at diagonally opposite WWLLN sites, the standard deviation of each individual time of group arrival should be $10/\sqrt{2}$ μs. The location error in km per microsecond of time-of-group-arrival error (assuming this to be the residual error) is hence $1.5\sqrt{2}$ km divided by $10/\sqrt{2}$ μs, which is c, the speed of light, 0.3 km/μs. This is deduced for a stroke in the center of a square defined by four WWLLN sites, the times of group arrival at which have the same error standard deviation, resulting in a purely radial error standard deviation (the same in all directions).

Thus, at least for the special center-of-square model, the relationship between the location error and the residual error is simply *c*, the speed of light. Is this true for every point inside the square?

To check this, we considered a large array of points in the square. At each point in the square, we moved the "lightning stroke" by small but random displacements of *x* and *y* such that the radial displacements had a normal distribution of a given standard deviation that was the same for all points, while all displacement directions were uniformly represented. This also showed that the relationship between the location error and the residual error is simply *c*, the speed of light, at all points inside the square.

This process was also used to make the map shown as Figure 2. This map extends in latitude from Antarctica to beyond the Arctic, and in longitude to include all of Asia. It shows the original six lightning-location sites (black-filled circles) of what was to become the WWLLN. Following the red lines clockwise from the right-most, the sites are Dunedin, Perth, Singapore, Osaka, Darwin, and Brisbane. For each point of the map, the time of group arrival at each of the six sites of a sferic (from a stroke) at that point was calculated. Taking this point and the resulting times of group arrival as a reference, the "stroke" was moved randomly in distance and direction about that point. The standard deviation of the radial displacement required to make the residual error equal 5 μs was recorded as a color shown on the scale.

The highest location accuracy was for strokes inside the area bounded by the red lines, where the error was ~1.5 km, which was *c* (0.3 km/μs) times the residual error (0.5 μs). This demonstrated that the *location error is* c *times the residual error provided the lightning occurs inside the area bounded by the sites receiving it.* Using the yellow line as a boundary, giving a trapezoidal shape to enclosed area, the location error was nearer 2 km at the SE end near Dunedin. This was reasonably consistent with our (center-of-a-square) model, which would have an error of ~2km. The important feature of Figure 2 is the way the accuracy changed outside the area bounded by the lines: the area surrounded by the lightning sensors.

The decrease in accuracy (increase in location error) changed slowly outside the midpoint of a boundary, but quickly outside a corner (a receiving site) of the bounded area, depending on the sharpness of the corner. The angles at Perth and Singapore are ~120°, and showed a moderately sharp drop-off. The angle at Osaka is ~60°, which gave a sharper drop-off, while that at Dunedin is ~30°, which gave a very sharp drop-off in accuracy, and so an increase in error, in a distance of a few km. This was consistent with our one-dimensional world, where the location of a stroke not between A and B had no accuracy (unlimited error).

All WWL locations now made available are of lightning strokes surrounded by active WWLLN sites, and have residual errors < 30 μs, corresponding to rms location errors < 9 km. The residual errors were obtained from the down-hill simplex method. This provides a built-in accuracy measure (*provided the lightning strokes are surrounded by WWLLN sites*). Location using only three WWLLN sites, while not allowed by the down-hill simplex method and

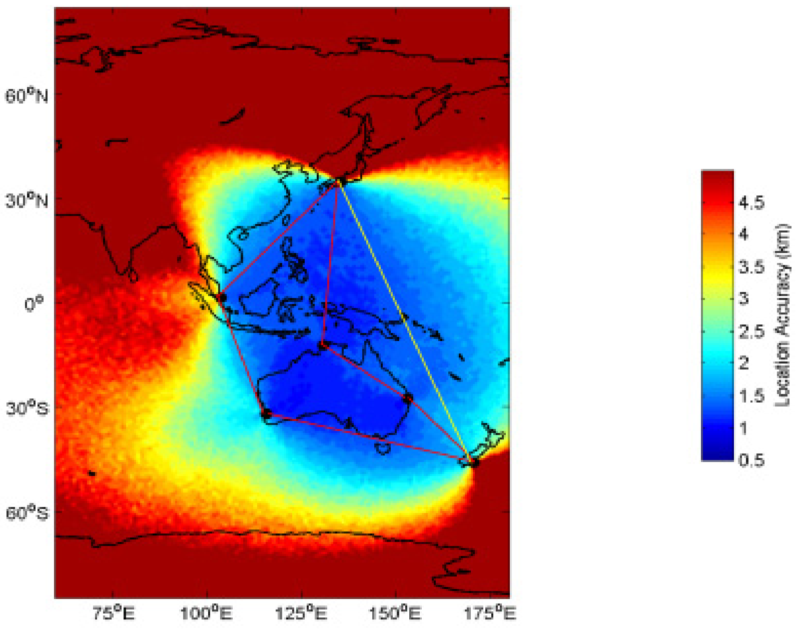

Figure 2. A calculation of the location accuracy of lightning strokes at any point on the map, assuming that each stroke was detected by all six receivers (black dots), and that the residual error was 5 μs at all points. Only inside the area bounded by the red lines was the location error determined by the residual error. The location error increased very sharply outside of sharp corners.

which gives rise to location ambiguities using any time-based method, provides no accuracy measure: an error in one time of group arrival simply results in a different location, with no indication of it being erroneous. The minimum for the down-hill simplex method is four WWLLN sites, but we found that the data quality was significantly improved by requiring more than four WWLLN sites. This loses weak strokes that are detected by the four nearest WWLLN sites but not by a fifth and more distant WWLLN site.

The relationship between the radial rms location error, Δr, and the residual error, Δt, is simply $\Delta r = c\Delta t$, where $c = 0.3$ km/μs, *provided* the lightning stroke is surrounded by lightning sensors. This requirement means that the lightning stroke is inside the perimeter defined by the polygon of the WWLLN sites that detected the stroke. We test for such "surroundedness" by calculating (by spherical geometry) the direction from the lightning location to each lightning sensor used in the location. The range of directions must exceed 180° or else the location is rejected. Thus, all lightning locations provided to anyone have passed this test, in which case the relationship above can be used in reverse to find the error in the time of the lightning stroke, which is therefore the residual error. To see this, suppose the residual error is 30 μs, so the rms radial error is 9 km. In determining the lightning location, we begin at the lightning sensor that had the earliest time of group arrival (the first WWLLN site to receive the lightning stroke). Call that site A. By GPS, we know the position of A to within a few meters, and we know the time of group arrival to within a few microseconds: let's suppose we know the time of group arrival exactly. To determine the time the lightning stroke occurred, which must be earlier than reception at A, we must subtract the time for travel from the stoke to A (at the group velocity). However, the distance is uncertain by 9 km, so the travel time is uncertain by 30 μs. Thus, Δt is equal to the residual error, in this case 30 μs.

It is important to note that the necessity of "surroundedness" for adequate accuracy is not specific to the WWLLN. It applies to all lightning location networks that use timing alone for location.

6. Detection Efficiency

A global network has the advantage of no boundaries – every position a lightning stroke could happen at is surrounded by receiving sites – which appears to avoid the problem we had when lightning strokes as far away as Africa or America from our six-station network could be detected but not accurately located. However, this ignores some problems. First, the ice cover on Antarctica (up to 4 km deep) may be a barrier to VLF propagation across it. This means that the two WWLLN sites in Antarctica (Rothera and Davis) are vital for location of lightning south of the southern continents. Second, temporary outages of one or two WWLLN sites are not uncommon, so although a lightning stroke maybe surrounded by WWLLN sites, outages of one or two might reduce the number of active sites to less than the minimum required for location. Third, a lightning stroke must be strong enough to be detected by this minimum (currently set at five) after travel of several thousand kilometers.

Although the WWLLN covers the whole world, we must limit the number of lightning strokes detected by each WWLLN site for two reasons. The first is to reduce the probability of a bunch of sferics arriving over a period of 30 ms not being from the same lightning stroke. If we increase the sensitivity to detect all sferics, the overlap would remove any pattern of bunches of sferics. We currently achieve this by limiting reception to an average (over a minute or so) of about three sferics per second. Since we reduce the detection rate by raising the detection threshold, this means we detect the strongest 300 sferics in a period of 100 seconds (we put it like this because only the *average* detection rate is three per second). The computer at each WWLLN site analyses each set of 64 samples grabbed. If on analysis this set shows zero or false Earth-ionosphere waveguide dispersion, it is rejected as spurious, and does not affect the automatic threshold control setting.

Each WWLLN site has its automatic threshold control set so that it detects an average of three sferics per second, all of which pass the tests and which exceed the amplitude threshold. During the decade or so when Omega was the global navigation system (it used the VLF band, as does the WWLLN), Omega receivers occasionally reported all eight transmitters. VLF communications signals have been observed to travel the "long way around" (e.g., 30 Mm instead of 10 Mm) [10]. This may also happen in the WWLLN, so we reject lightning locations from a set of times of group arrival if they include one corresponding to an Earth-ionosphere waveguide travel beyond 13.3 Mm (one-third the way around the Earth). This limit is imposed lest the actual travel is the long way around (26.7 Mm) at much lower attenuation.

From this, we concluded that each WWLLN site detects an average of three lightning strokes per second from distances up to 13.3 Mm (one-third the way around the world). This corresponds to 75% of the world's surface where lightning happens, so that the WWLLN has access to an average of four lightning strokes per second from the whole world (deduced from 3/s from 75% of the world). If all these were located, it would be the maximum possible, so in this sense the efficiency would be 100%.

During the 31 days of May, 2007, the number of lightning locations by the WWLLN during each day ranged from 123,471 on May 28, to 233,962 on May 13, corresponding to 24 hour averages of 1.43/s and 2.71/s, respectively. The average over the whole month was 1.75/s. In terms of the maximum possible of locating every stroke accessible to WWLLN (4/s), the efficiency ranged from 36% (May 28) to 68% (May 13), with the May average of

44%. Taking the global flash rate [5] as 100/s (all flashes with peak currents >1 kA), then 4/s implied the strongest 4% of flashes. About 4% of flashes have peak currents >70 kA [2], so we might claim that WWLLN locates about 45% of flashes having peak currents above 70 kA.

We stress that the WWLLN was never intended to locate all lightning, so the conventional definition of "efficiency" has little relevance. On the other hand, we have introduced checks to exclude from our records any lightning locations that do not meet our standards of accuracy.

7. World Map

Figure 3 is a four-panel world map. Each panel is the whole world on the same day (May 1, 2007), and shows the 30 WWLLN sites from left to right (increasing longitude): Honolulu, Tahiti, Seattle, LANL, Mexico, Peru, MIT, Rothera; Puerto Rico, Cordoba, Sao Paulo, Ascension I, Lisbon, Sheffield, Budapest; Hermanus, Sodankyla, Durban, Tel Aviv, Moscow, Davis, Lanzhou; Singapore, Perth, Darwin, Osaka, Kingston, Brisbane, Dunedin, Suva. These are separated in this list by commas, except that where two sites in this list have nearly the same longitude but are in opposite hemispheres (e.g., Rothera; Puerto Rico), they are separated by semicolons. These sites are indicated by white circles, inside of which is red asterisk if that site was active at that time. Only one site (MIT) was inactive, and that was only at 00:00 UT.

Each panel shows a 40-minute period prior to 00:00 UT, 06:00 UT, 12:00 UT, 18:00 UT. The 40-minute period was divided into four periods of 10 minutes by the color of the lightning strokes, which are shown as dots. Those occurring during the latest 10 minutes, ending in the time shown in the heading of the panel, are blue and larger. For example, the bottom-left panel shows strokes occurring during the 40 minutes from 11:20 UT to 12:00 UT. Those occurring during 11:20 to 11:30 are red dots, those occurring during 11:30 to 11:40 are yellow dots, those occurring during 11:40 to 11:50 are green dots, and those occurring during 11:50 to 12:00 are larger blue dots.

The colored dots were plotted in reverse order, obscuring later dots plotted beneath: first the most recent (large blue, 240 km diameter as measured on the surface of the Earth, so the dot diameter can be used as a scale), then the smaller green, yellow, and red (all 120 km diameter), in that order. If there was a lightning stroke in the same place in each of the four 10-minute periods, the large blue dot appears with the red dot in its center. If all were precisely in the same place, the red dot would hide the green and yellow dots. When the alignment was not within 15 km, the yellow dot was not completely obscured (but may obscure the green dot), so a thin (15 km, corresponding to one pixel) crescent is visible. An example is shown in Figure 4.

The terminator, the sunrise-sunset curve, is a great circle, but appears on this projection as a quasi-sinusoidal white curve. The grey part is the part of the Earth's surface

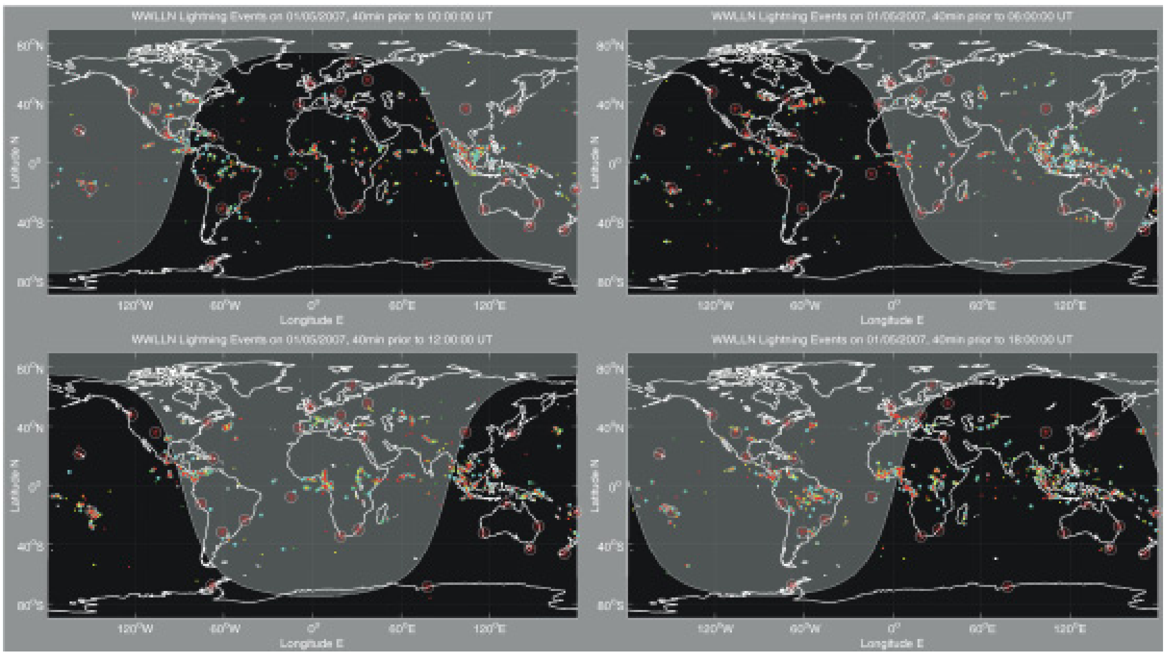

Figure 3. A four-panel world map. Each panel is the whole world on the same day (May 1, 2007), and shows the 30 WWLLN sites indicated by white circles, inside of which is a red asterisk if that site was active at that time. Only one site (MIT) was inactive, and that was only at 00:00 UT. Each panel shows a 40-minute period prior to 00:00 UT, 06:00 UT, 12:00UT, 18:00 UT. The 40-minute period is divided into four periods of 10 minutes by the color of the lightning strokes, which are shown as dots. Those occurring during the latest 10 minutes, ending in the time shown in the heading of the panel, are blue and larger. For example, the bottom-left panel shows strokes occurring during the 40 minutes from 11:20 UT to 12:00 UT. Those occurring during 11:20 to 11:30 are red dots, those occurring during 11:30 to 11:40 are yellow dots, those occurring during 11:40 to 11:50 are green dots, and those occurring during 11:50 to 12:00 are larger blue dots.

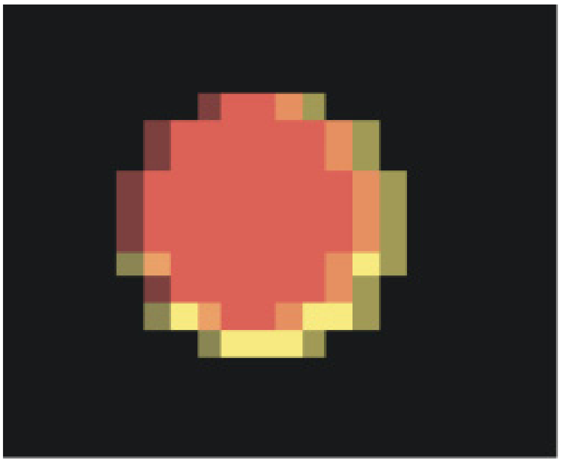

Figure 4. Strokes 10 minutes apart but only 15 km apart in location.

in daylight, while the black part is at night. Note that in all figures, including those below, the terminator moves left with time. If night (black) is on the right side, the terminator marks sunset. If night is on the left side, the terminator marks sunrise. Figures 4, 5, and 6 have all been made from Figure 3 by expanding the PDF of Figure 3, making a screen shot of the section required, and suitably cropping it. This is to illustrate the versatility of the WWLLN world maps, but for serious research, one requires the tabulated data.

At this time of the year (May 1, about six weeks after the equinox), it was spring in the northern hemisphere, and autumn (fall) in the southern hemisphere. Above 80° N, it was continuously sunlit, and it was continuously nighttime at southern latitudes south of 80° S. Lightning at mid-latitudes over land tends to be most common in the local summer. This time of the year is spring for the USA and Europe, and autumn (fall) for Australia. At low latitudes near the equator, there is always lightning, mainly on the summer side.

In middle latitudes, lightning over land tends to occur in local late afternoon and early evening. The top-left panel shows the world at 00:00 UT, and so it was local midnight in England and west Africa, but near sunset in the Americas. Lightning appeared in the Amazon basin, and also in the USA south of the Great Lakes, west of Boston. The bottom-left panel shows the world at 12:00 UT, and so midday in England and west Africa, but near sunrise in the Americas. There was almost no lightning in the Amazon basin or over land in the USA, although there was a bunch of lightning over the Atlantic Ocean about 1500 km east of Boston.

All panels showed lightning near Panama at all times of the day. A similar lack of diurnal variation appeared in the Indonesian archipelago and equatorial Africa. However, closer examination showed that near sunrise, the lightning tended to occur over the sea, while near sunset, the lightning tended to occur over land. This is illustrated at these times in Figures 5 and 6.

As seen on all four panels of Figure 3, lightning in the mid-Pacific was common near Tahiti. Winter lightning was virtually non-existent over mainland Australia, but common over the 2000-km wide Tasman Sea, between Australia and New Zealand. There was clear evidence that strokes over sea were often stronger than strokes over land, thus winter lightning over both the Japan Sea and the Pacific Ocean near Japan was frequently strong enough to trigger sprites (optical phenomenon requiring darkness to observe) and trimpis (localized ionospheric perturbations) [11]. The study of positive and negative strokes over the Gulf Stream showed that lightning over the ocean was more intense than over the North American continent [12].

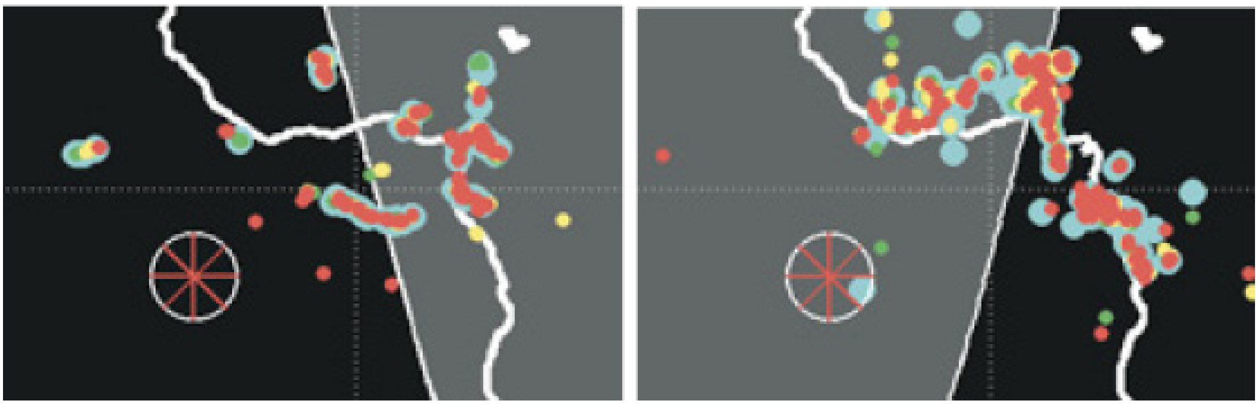

Figure 5. Enlarged sections from the panels of Figure 3, showing the equatorial West Africa coast. The WWLLN site is Ascension I. The left panel was at 00:60 UT, which was also local time. The terminator marks sunrise and crossed the equator (horizontal line) where the zero meridian (longitude = 0°) intersected the equator. The grub shape of lightning locations over the sea spread in time over the full 40 minutes and over the sea by a few hundred km. In each of over 10 positions, at least one, but probably several, lightning strokes occurred in each of the four 10-minute periods. In the right panel, the terminator marked the sunset. The time was 18:00 in both UT and local. This enlargement was also taken from Figure 3 (the 18:00 UT panel). In this case, there was more lightning, and most of it was over land, just inland from the coast.

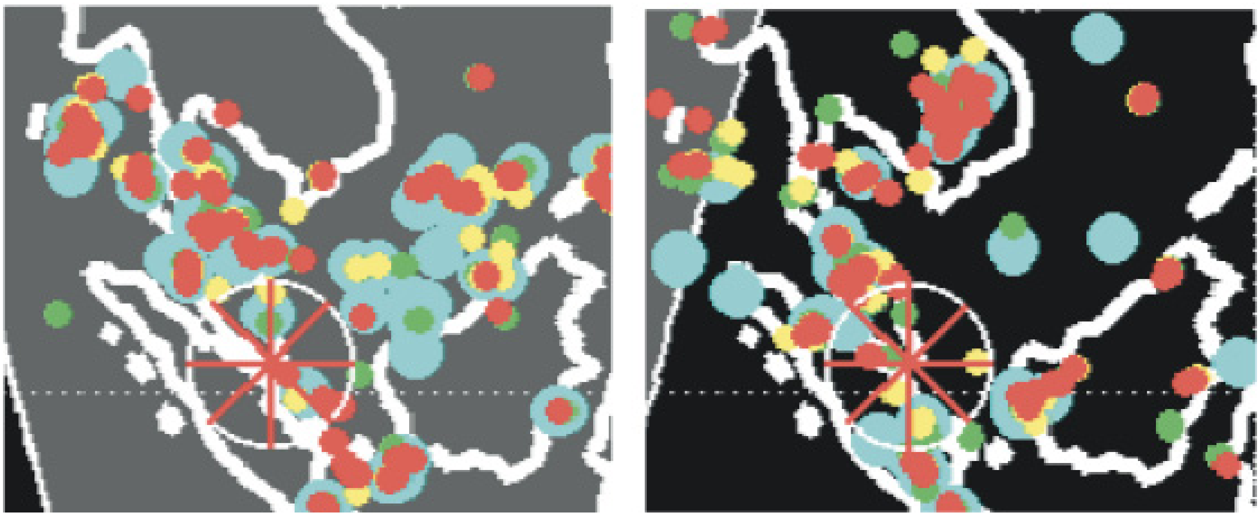

Figure 6. Sections from the 00:00 UT and 12:00 UT panels of Figure 3, enlarged more than in Figure 5. The dotted horizontal line is the equator, 120° E longitude is the right-hand border of both panels, and the WWLLN site was Singapore. Local solar time spanned from 6 am (sunrise) to 8 am for the left panel, and 6 pm (sunset) to 8 pm for the right panel. The three main landmasses are Thailand-Vietnam (upper left), Indonesia (lower left), and Borneo (lower right). As in Figure 5, lightning was mainly over the sea at 7 am and over land at 7 pm.

Winter storms over the eastern coast of the Mediterranean showed a similar diurnal variation, as seen in Figures 5 and 6 for equatorial regions (where there is no winter). The maximum in lightning activity over the sea was at 0500 LST (local solar time), and over land at 1300 LST [13].

As explained above, the WWLLN locates only strong lightning (peak currents > 70 kA), so lightning locations over sea might feature more prominently in WWLLN data than in other lightning-location systems. This is mainly because land-based MF systems cannot accurately locate lightning over sea unless the sea is surrounded by the system, but partly because such systems locate lightning with peak currents over 5 kA, which amount to 80% of lightning [10].

It is perhaps surprising how much can be seen on a single day on the world map: the diurnal and seasonal variation of lightning occurrence over land at mid-latitudes; the very different, almost anti-phase diurnal and seasonal variation of occurrence over the sea; and curious lightning occurrences over mid-ocean.

8. A Summary of Research Results with the WWLLN

We consider these results under three categories: regional detection efficiency, global network coverage of tropical "chimneys," and targeted geophysical/meteorological studies.

Study	Location	Local Network	Detection Efficiency	Qualifications
[14]	Brazil	Brazil Integrated Network (BIN)	0.3%	CG flashes
[15]	Australia	Kattron	1%	CG flashes
[16]	Australia	Kattron	25%	Single day (IC+CG flashes)
[17]	USA	Los Alamos Sferic Array (LASA)	4%	$I_p > 40$ kA
[18]	New Zealand	New Zealand Lightning Detection Network (NZLDN)	1% 5.4% 10%	IC flashes (IC+CG flashes) $I_p > 50$ kA
[19]	Six regions	FORTE (satellite)	0.7%	FORTE (IC) WWLLN (CG)

Table1. A summary of studies on local WWLN detection efficiency

8.1 Regional Detection Efficiency for the WWLLN

A number of investigations have combined local lightning-network observations [14-19] to make estimates of the detection efficiency of the WWLLN in these regions. These were primarily for ground flashes, but the last of these used lightning observations from space. Key aspects of these studies are summarized in Table 1. In judging the significance of these numbers, certain qualifications need be considered, as summarized in the final column of the table. The initial investigation by Lay [14] was characterized as a "worst-case scenario" because it was undertaken in Brazil, where the WWLLN network coverage at that time (and see Table 2) was quite limited. The detection efficiency for ground flashes was found to be 0.3%. This study also first identified the increase of WWLLN detection efficiency with lightning peak current.

In later work by Rodger [18] in New Zealand, the detection efficiency was found to be larger by an order of magnitude in the Eastern Hemisphere, where the WWLLN station density is maximum (see Table 2) [16, 18]. Rodger also estimated the detection efficiency for IC (intracloud) strokes with the New Zealand Lightning Detection Network, and found that 10% of these events were detected by the WWLLN [18].

Jacobson [17], using both the Los Alamos Sferics Array (LASA) and the National Lightning Detection Network in the US, showed detection efficiency as a function of lightning peak current. This indicated an asymptote at about 4% as peak current continued to increase. These results suggest a problem with data processing rather than signal strength in further improvements of detection efficiency toward the long-term WWLLN goal of 50% for cloud-to-ground lightning [15].

The most recent study in detection efficiency [19] used a satellite platform for comparison. The detection efficiencies (WWLLN/FORTE) in Table 1 are lower than other results in the table, simply because the FORTE satellite is a superior detector of intracloud lightning, whereas the WWLLN is a superior a detector for ground flashes. In all other studies in Table 1, ground-flash networks were used as "truth."

8.2 Global Network Coverage

One important measure of this network's success at worldwide lightning location is in its documentation of the Earth's most prominent regional lightning features: the tropical "chimneys." These three prominent land regions – the Maritime Continent, Africa, and the Americas – figure prominently in the modulation of the global electrical circuit [20] and the "Carnegie Curve" of atmospheric electricity. Analysis of global thunder days [21] and the satellite optical measurements [22-24] have shown a consistent climatological ranking of the lightning counts, with Africa generally dominating, and the Maritime Continent (despite its large area) in third place.

Three well-defined spatial maxima in lightning were apparent in all global maps produced by the WWLLN since 2004, but the measured relative strengths of the three maxima were clearly influenced by the heterogeneity of station locations. The maturation of the WWLLN over time was quantified in a series of publications [15-18]. These results are summarized in Table 2, which also includes the number of stations in the Eastern and Western Hemispheres over time.

The station density in the Eastern Hemisphere (where the network originated, in New Zealand) has dominated from the outset. In the first WWLLN study [16] to produce a global map, the lightning in the Maritime Continent dominated that in South America (where the continental station density was least) by a factor of two. In the most recently published global map [18], using more than four times as many stations in the Western Hemisphere as in 2004, the Americas increased in relative importance, and were showing ~80% as many flashes as the Maritime Continent. Africa, the dominant lightning chimney in other studies, remained in third place with the most recent network configuration, but only a single WWLLN station was then in place within the African continent.

The foregoing results and the general requirement that five stations be involved in a reliable WWLLN network lightning location make it apparent that more-uniform station density is needed for representative global mapping of lightning flashes, at least with data-processing methods currently in place. However, network expansion is currently in the works toward remedying this situation.

Year	Eastern Hemisphere	Western Hemisphere	Reference
2004	9	2	[15]
2005	12	6	[16]
2006	14	6	[17]
2006	13	9	[18]

Table 2 . WWLLN Expansion/ Station numbers by year and hemisphere

8.3 Targeted Geophysical and Meteorological Studies with the WWLLN

Several recent publications have made use of the WWLLN as the main observational component of the investigation [25, 19, 26-28]. These studies are reviewed in turn.

Holzworth et al. [25] investigated the role of lightning in the global electrical circuit. Comparisons of the vertical current density in the stratosphere over Antarctica with integrated WWLLN lightning counts were made over a two-week time interval. These two continuous time series were dominated by a pronounced diurnal variation in both quantities. The diurnal variation of current density varied by more than a factor of two, in contradiction to other results on the diurnal variation of the global circuit [29]. The measured correlation was undoubtedly dominated by the pronounced diurnal signal in both quantities. Phase comparisons over the UT diurnal cycle were problematic because of the present heterogeneous coverage of the three tropical chimneys by the WWLLN, as discussed earlier. Further studies of this kind will be valuable when a more-uniform station density is achieved, so that correlations for individual tropical chimneys are possible.

Lay et al. [19] subdivided the globe into six large regions to investigate the relative local diurnal variation of lightning activity with WWLLN observations. Despite the evidence that the majority of WWLLN detections were larger-than-average-peak-current flashes to ground, the general diurnal amplitude variations and phase of these measured variations were broadly consistent with results in other studies involving both ground-based observations of CG (cloud-to-ground) activity [30] and satellite-based observations of total lightning activity [31]. For land, regions the amplitude variations were pronounced (factors of five to 10), with maxima consistently in the late afternoon, in agreement with the classical analysis of the global electrical circuit using thunder day data [20]. Regional variations in the phase of maximum activity were apparent, and were likely related to the variable mix of convective and mesoscale thunderstorms. The oceanic records in all six regions had comparatively flat diurnal amplitude variations, consistent with other studies on total lightning activity observed from space [31, 22].

Ortega and Guignes [26] made valuable use of the WWLLN coverage over the Pacific Ocean (where lightning documentation is unavailable from other networks) to investigate the seasonal and inter-annual behavior of the South Pacific Convergence Zone. This major tropical convective feature, extending zonally for sixty degrees of longitude, is an extension of the inter-tropical convergence zone in the western Pacific Ocean. The seasonal variation of lightning features generally followed the seasonal variation in rainfall, with maxima in the southern summer, consistent with the South Pacific Convergence Zone's southern hemisphere prominence. The WWLLN-observed lightning activity tended to be associated with more-moderate rainfall rates. On the inter-annual time scale, four years of WWLLN observations showed this long band in the warm El Niño phase. This behavior was consistent with inferences drawn from Schumann-resonance observations [32-33] concerning the inter-annual variations in the latitudinal position of the global tropical lightning over the ENSO (El Niño-southern oscillation) time scale.

Solarzano et al. [27] also exploited the oceanic lightning coverage provided by the WWLLN to investigate lightning variations in tropical cyclones. As with other studies over oceans with land-based VLF networks [34], the lightning in hurricanes and typhoons was comparatively rich for this special mode of oceanic convection. The spatial resolution of the WWLLN was just adequate to distinguish lightning origins in the convective eyewall region and in the outer rain bands. The rain bands were shown to be the dominant feature in the lightning production from such storms, and this was perhaps consistent with the evidence that the predominant WWLLN target is high-peak-current ground flashes. The phase relationships shown there between bursts of electrical activity and the deepening of these storms were somewhat less well defined than what was demonstrated recently with LASA observations [35] and additional unpublished observations by Los Alamos National Laboratory. This was probably because intracloud lightning was more prevalent in this data set, and is a consistently better indicator of convective development.

Despite the evidence for under-representation of African lightning activity in the current WWLLN station configurations [18-19], Price et al. [28] identified an interesting precursory signal in East African lightning several thousand kilometers upstream of hurricane activity off the west coast in the Atlantic Ocean, by examining daily flash counts there. Given the well-established westward progression of storm systems in African easterly waves (AEWs), these results supported new ideas that the origin and maintenance of the African easterly waves are more clearly tied to the moist convection within them than to the baroclinic instability of a zonal jet [36]. This study by Price et al. [28] was included in *Discover* magazine's list of 50 most important findings in 2007.

9. Conclusions

The WWLLN covers the whole world with a single set of lightning sensors and redundant lightning data processors, all having the same design and software. The use of VLF propagation in the Earth-ionosphere waveguide allows detection of strong lightning strokes, up to the imposed limit of 13.3 Mm (one-third of the way around the world).

Using only the VLF electric field allows such lightning detection in urban areas on a 1 m whip antenna with adequate signal-to-noise ratio. All of the WWLLN sites are on university or research-institute campuses, observatories, or Antarctic bases. Using the entire globe, there are no borders to the area covered, so all lightning strokes are surrounded by lightning sensors, but not all strokes are detected by surrounding sensors. All lightning strokes located by the WWLLN are tested for such "surroundedness." Locations failing the test are rejected.

The continuously available WWLLN observations have also been profitably used in a number of scientific investigations for meteorological/lightning context. These cases include the observation of an unusual transient luminous event from the NASA Space Shuttle [37], the incidence of lightning-generated whistlers propagating between conjugate points in Europe and in Africa [38], the documentation of a sprite-producing storm in the lee of the Andes in Argentina [39], the application of lightning sensing to the warning of severe weather [40], the characterization of sprite-parent lightning flashes in wintertime over the Mediterranean Sea [41], the initial detection of sprites over China [42], the documentation of a negative ground flash causal to a sprite-halo [43], and as a proxy global map of sprite activity [44]. The convenient use of the WWLLN as support for these and other kinds of analyses is expected to continue and expand.

10. References

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XXIXth General Assembly

BUSINESS TRANSACTED BY COMMISSION A

Acting Chair: Dr P. Banerjee

1. Commission A Business Meeting 1, Monday 11 August 2008

Dr P. Banerjee called the Business Meeting 1 to order at 1720 Hrs. Those present introduced themselves giving their name and affiliation, and added their details to the list of participants. 16 members and 10 voting members were present.

1.1 Approval of agenda

Dr P.Banerjee proposed an agenda for the meeting. The agenda was approved unanimously.

1.2 Election of new Vice Chair

Dr. Schlegel, past president of URSI attended the meeting to help Dr. Banerjee to conduct the election of Vice Chair.

There were four candidates for the post of Vice Chair. They were

1. Nuno Borges Carvalho (Portugal) (could not attend the meeting)
2. William A. Davis (USA))(was present)
3. Min Liu (China CIE) (could not attend for not getting visa to enter USA)
4. Andrew Charles Marvin (UK) (was present)

Dr. Banerjee showed the biodata of all four candidates one by one through the LCD projection.

The Acting Chair had received 5 ballot papers by mail prior to the meeting. Received ballots were confirmed by respective representatives those were present in the meeting. The other voting members voted by paper ballot at the meeting. The ballots were counted by the Acting Chair and Dr. Schlegel. The result was:-

1. Nuno Borges Carvalho (Portugal)	10
2. William A. Davis (USA)	17
3. Min Liu (China CIE)	3
4. Andrew Charles Marvin (UK)	11

Dr. Schlegel left the meeting immediately after the election process was over. The members expressed thanks to Dr. Schlegel for his help and for sparing his time.

Young Scientist Party was supposed to be attended by the Chairs of all ten commissions. To attend the party the Business Meeting was supposed to be ended by 1800 hours. So no other agenda could be taken up.

The Chairman adjourned the meeting at 1800Hrs.

2. Commission A Business Meeting 2, Wednesday 13 August 2008

Business Meeting 2 was started at 1720 Hrs. Those present introduced. 13 members were present.

2.1 Approval of agenda

Dr Banerjee proposed an agenda for the meeting. The agenda was approved unanimously

2.2 Summary of Council Meeting of August 12, 2008

The Chairman informed the audience of the outcome of the election of the Chairs and Vice-Chairs of the URSI Commissions. The council approved the election of Dr. William A. Davis as Vice Chair and Dr. P.Banerjee as Chair of Commission A at the meeting of August 12, 2008.

- There were only 62 papers in Commission A out of total paper of 1456 in the current GA. This reflects that there was lack of encouraging response from Commission A. There was discussion on how to increase Comm A participation. Dr. Banerjee requested members to generate awareness of URSI in their respective countries and promote activities on Electromagnetic metrology. This effort would make the participation in URSI GA more useful and meaningful. It is also desired that all delegates interested in commission should attend the business meeting.
- Associate editor for the Radio Science Bulletin for Commission A: should be the duty of the vice chair. There should be more contribution from Commission A for the bulletin -at least 2 papers per commission per year.
- URSI would like to increase visibility. URSI has selected to develop white papers on areas of impact to society. (EM effects on human health and Power from Satellites are two examples)
- URSI formed a long-range planning committee to develop long-term goals from each commission to have an impact on the society. Long-Range planning committee composed of past chairs. Prof Cannon has been selected the chair for 2008-2011.
- the Chairman informed the members that there were three (3) countries bidding for the venue of the 2011 URSI GA e.g. China (CIE), Sweden and Turkey. Venue is to be decided at the Council meeting of August 14, 2008.

2.3 Topics of discussion

The website of commission A has been a longstanding issue. Dr Davis kindly offered to host a Web-site for Commission A. He gave a detailed presentation on his plan. This was followed by a discussion. All members of the Commission are expected to contribute to the site.

2.4 Activity Reports of Members

a. Portugal organizes National symposium on URSI matters
   - Last year had participation from Spain.
   - This year it is being tried to get participation from Africa and Brazil.
b. Dr. Banerjee asked to report country activities to the chair and to others.
c. France Published "Measurements in Electromagnetics," part of a series for URSI. More information on this should be given to the chair.
d. Italy will also have a meeting in 2012.
e. Belgium and Netherlands are having joint meetings every 2 year. The next meeting in 2010 focuses on nonlinear device measurements.

2.5 AP-RASC 2010

Dr. Hosokawa of Japan informed the members that Asia Pacific Radio Science Conference (AP-RASC 2010) would be held in Toyama, Japan 2010. AP-RASC of 2007 was postponed by Australia.

2.6 Discussion on Technical sessions of Next GA

Chairman requested all members to make spadework for discussions on the themes of Technical sessions of Next GA. The skeleton of technical programme for Commission A may be worked out in the Business Meeting 3.

2.7 AOB

No other business was tabled. Chairman adjourned the meeting at 1815 Hrs.

3. Commission A Business Meeting 3, Friday August 15, 2008

The Business Meeting 3 was started at 1720 Hrs with the introduction of members. 11 voting members were present.

3.1 Approval of Agenda

Dr Banerjee proposed an agenda for the meeting that was accepted unanimously.

3.2 Report of Council Meetings

Dr. P.Banerjee reported the result of the venue of 2011 to be Istanbul, Turkey.

A note submitted by Dr. E. Bava past Chair of Commission A was read out by Dr. Banerjee in the meeting for the consideration of members.

" At the international level it has been recognized that, beside the traditional metrology mainly concerned with measurements of physical quantities, new areas have emerged where measurement methodology, improved accuracy and traceability are needed. These areas are health, ambient and climate where measurements rather complex are required and electromagnetic metrology already plays an important role".

Moreover the International Committee of Weights and Measures (CIPM) has recommended that the National Metrology Institutes increase their efforts in the determination of a few fundamental physical constants in view of a possible decision, to be taken at the next General Conference of Weights and Measures (CGPM) in 2011, on new definitions of SI fundamental units based on fixed values of physical constants.

Moreover at the European level a coordinated research program has recently started organized along 4 targeted programmes:

1. <u>fundamental metrology</u> including determination of fundamental <u>physical constants</u> and <u>optical frequency standards</u> and <u>optical frequency comparisons</u>
2. <u>health</u> including <u>diagnostics, therapy</u> and <u>biotechnology</u>
3. <u>mechanics</u> including <u>nanotechnology</u>
4. <u>electromagnetics</u> including <u>nanotechnology</u>

The above description suggests that links with Commissions D, E and K should be maintained and possibly strengthened. Moreover the proposed joint session on optical standards with Commission D is a positive proposal, however this JAD session does not fit completely the important topics of Comm. A

a. expected new results obtained with Cs fountains operation at liquid nitrogen temperature (accuracy 10^{-16}?)
b. contributions of metrology to science such as determination of physical constants (not only those of interest for a redefinition of SI units) "

3.3 Discussion on Technical sessions of Next GA

The outline/programme of 2011 GA was presented by Dr. Banerjee. Many joints sessions like AC, AB, AD, AG AKC, AJ and AE are being planned. Dialogue with many of the chairs has been initiated. It has been felt that Joint sessions will generate better participation and interest. Skeleton of Technical programme for 2011 GA emerged as

AC	Measurement related to Wireless Communications
AE	EMC Measurements
AB	Antenna Measurement
AD	Optical Metrology
AK	EM Exposure and Human Health
AJ	Pulsar Timing/VLBI
AG	Ionosphere in GNSS Timing
A	EM Materials
A	Time Scale Generation and Distribution
A	Quantum Standard
A	Nano Metrology
A	THz Measurements
A	Microwave Measurements

Based on the above plan the final programme will be evolved.

3.4 AOB

Dr Banerjee on behalf of members of Commission A thanked all session's conveners for their excellent cooperation and all speakers for their kind participation in Commission A.

No other business was tabled. The Chairman adjourned the meeting at 19:00.

BUSINESS TRANSACTED BY COMMISSION B

Chair: Professor Lot Shafai
Vice-Chair: Professor K.J. Langenberg

Comission B held two Business Meetings on Monday, August 11th and on Wednesday, August 13th.

1. Student Awards at the URSI GA

Five Student Paper Prizes have been awarded to:

1. Christian Sohl for paper #1162 “Some Paradoxes Associated with a recent Summation Rule in Scattering Theory”by C. Sohl, M. Gustafsson, A. Bernland, Lund University, Lund, Sweden.
2. Yvonne Weitsch for paper # 1651 “A Non-Radiating Composite Right-/Lefthanded Transmission Line derived from Substrate Integrated Rectangular Hollow Waveguide” by Y. Weitsch, T.F. Eibert, Universität Stuttgart, Stuttgart, Germany.
3. Thomas H. Hand for paper #1856 “ Controllable Magnetic Metamaterial using Digitally Addressable Split-Ring Resonators” by T.H. Hand, S.A. Cummer, Duke University, United States.
4. Jurgen de Zaeytijd for paper #2415 “Three-Dimensional Linear Sampling applied to Microwave Breast Imaging” by J.G. De Zaeytijd, C.L. Conmeaux, A. Franchois, Ghent University, Ghent, Belgium.
5. Taeyoung Yang for paper #2769 “The Design of Ultra-Wideband Antennas with Performance close to the Fundamental Limit” by T. Yang, W.A. Davis, W.L. Stutzman, Virginia Tech, United States

2. Vice-Chair Election

Two candidates for Vice-Chair have been nominated:

- Giuliano Manara, Italy and
- Man-Fai Wong, France.

Giuliano Manara has been elected (and approved by the Council).

3. URSI Commission B International Symposium on Electromagnetic Theory

Two bids to hold the triennial URSI Commission B International Symposium on Electromagnetic Theory in 2013 have been presented:

- Hiroshima, Japan
- Toulouse, France

Hiroshima has been elected.

The above International Symposium 2010 will be held in Berlin, Germany; Symposium location will be the Steigenberger Hotel.

4. Terms of Reference

The terms or reference of Commission B were extensively discussed during the previous General Assembly in New Delhi, therefore, no further changes have been proposed.

5. Commission B paper statistics for GA 2008

· Oral Session Papers 109
· Poster Session Papers 214
· Total Accepted Papers 323

5.1 Oral Sessions (B-Core)

· B01 – Electromagnetic Theory, 11 papers
· B02 – Scattering and Diffraction, 10 papers
· B03 – Inverse Scattering, 7 papers
· B04 – Antennas and Arrays, 10 papers
· B05 – Numerical, Asymptotic and Hybrid Methods, 7 papers
· B06 – Transient Fields and Ultra Wide Band Antennas, 7 papers
· B07 – Wave Field Imaging for Homeland Security, 7 papers

5.2 Oral Sessions (Joint Core)

· BCD – Physical Limitations of Electromagnetic Metamaterials, 8 papers
· BCK – Body Area Networks, 6 papers
· BK – Future Challenges of Computational Electromagnetics, 11 papers
· BKF – Stochastic Modeling and Uncertainty Management in Electromagnetics, 6 papers

5.3 Oral Sessions (Joint from other Commissions)

· HBDGJK – Solar Power Satellites, 7 papers
· EB – EM Modeling for EMC, 10 papers
· KBE – Biomedical Applications: Microwave Breast Imaging, 10 papers

5.4 Oral Sessions (New – Extra)

· B08 – UWB Antennas, 6 papers
· B09 – Compact and Wideband Antennas, 6 papers
· B10 – Frequency Domain, 7 papers

5.5 Poster Sessions

· General – BP1, BP2, …, BP23, 146 papers
· BPS1,BPS2, …, BPS5, 40 papers
· BDPS1, BDPS2, …, BDPS4, 28 papers
· HP – HBDGJK – Solar Power Satellites, 4 papers

5.6 Tutorial

Transmission Line Metamaterilals: Fundamentals and Applications, by George Eleftheriades and Ashwin Iyer, University of Toronto

5.7 General Lecture

Microwave Imaging in Medicine: Promises and Future Challenges, by Susan Hagness, University of Wisconsin-Madison

The triennial report given by B Chair Lot Shafai covered Meetings and Symposia (EMTS 2007, Ottawa, Canada; CNC/USNC 2007, Ottawa, Canada; URSI GA 2008, Chicago, USA) and Emerging Issues in Commission B (equal voting rights, inactive national chairs, Young Scientist support, Commission and URSI visibility, new scientific research areas, new applied research areas).

BUSINESS TRANSACTED BY COMMISSION H

Chair: Dr. Richard Horne
Vice-Chair: Prof. Y. OMura

1. Commission H Business meetings

Commission H Business Meetings were held three times during the GA on the following three occasions.

- Business Meeting 1: Monday 11 August 17:20 – 18:40 in room Grand F, chaired by Richard Horne
- Joint Business Meeting G & H: Wednesday 13 August 17:20 – 18:40 in room Grand E, chaired by Paul Cannon and Richard Horne
- Business Meeting 3: Friday 15 August 17:20 – 19:00 in room Grand F, chaired by Yoshiharu Omura

The chair of Commission H, Richard Horne appointed the vice-chair Yoshiharu Omura as the new Chair. Ondrej Santolik was appointed as the new vice-chair after voting from the member committees. The details of the votes are the followings: Ondrej Santolik (Czech Republic) 25, David Nunn (UK) 7; Meers Oppenheim (USA) 6, Craig Rodger (New Zealand) 9. The vice-chair has been confirmed to become an Associate Editor of Radio Science Bulletin.

2. Terms of reference of Commission H

No change required.

3. Abstract

The current form of abstract up to 1 page summary, optional 4 page paper was supported by the majority. The abstracts should be published in the form of CD and online.

4. Working Groups

Activities of the working groups related to Commission H were reviewed and their organization has been renewed as in the following.

4.1 Joint Working Groups

- *ABDFGHJK: An inter-commission working Group on Solar Power Satellites:* Co-chair for Commission H: K. Hashimoto (Japan), Co-chair for Commission G: K. Schlegel.
- *EGH: Seismo-Electromagnetics.* Co-chair for Commission G: S. Pulinets (Russia), H: M Parrot (France)
- *GH1 Active experiments in Space Plasmas*: Co-Chair for Commission G: Keith Groves (USA) (USA), Co-Chair for Commission H: B Thide (Sweden)
- *HEJ: Computer Simulations in Space Plasmas (*Co-chair for Commission H: Y. Omura (Japan), B. Lembege (France)

4.2 Inter-Union WG

- URSI/IAGA VLF/ELF remote Sensing of the Ionosphere and Magnetosphere (VERSIM), URSI Rep: H. Janos Lichtenberger

5. Science Session Proposals for 2011

- H1 Nonlinear waves and turbulence in plasmas, M. Oppenheim (USA), H. Usui (Japan) (TBC), and David Shklyar (Russia)
- H2: Wave-particle interactions and their effects on planetary radiation belts: Jacob Bortnik (USA), Craig Rodger (New Zealand), and Richard Horne (UK)
- H3: Micro/macro-scale kinetic processes at boundary layers in terrestrial and planetary environments: B. Lembège (France), G. Lakhina (India), and I. Shinohara (Japan)
- H4: Laboratory simulation of space and dust-related phenomena William Amatucci (USA) and Toshiro Kaneko (Japan)
- H5: Waves as signatures of neutral-plasma interactions in the environment of solar system bodies" , Christian Mazelle (France), (USA)TBC
- H6: Plasma waves and ion thrusters (R. Horne)
- H7: Open session (Y. Omura and O. Santolik) *
  Note: Because of the limited time slots for oral sessions at the next GA, the commission will decide later on reduction of the number of sessions.

6. Science Session Proposals for 2011 (joint with other commissions)

- HG1: Space-borne sounding and remote sensing of structures in the plasmasphere (active & passive)" (B.

Reinisch (G), R. Benson (H))
- HGB: Active experiments in plasmas with electric antennas and other means (Gordon James and Vikas Sonwalkar)
- GHE1: Lightning induced effects in the ionosphere and magnetosphere Com H. Victor Pasko
- GH1: Ionospheric modification, K. Groves(Com G.: USA) and B. Thide (Com. H: Sweden)
- GHE2 Seismo-electromagnetics, Com G: S, Pulinets, and Com H: M. Parrot
- HBDGJK: Solar Power Satellites Com H. Kozo Hashimoto

7. Proposed Meetings sponsored by URSI Commisison H

– ISSS-9, near Paris, France, July 3rd-10th 2009 Bertram Lembege (Mode B)
– International Chorus Workshop, California, Feb, 2009 Bruce Tsurutani
– VERSIM, Hungary, September, 2008 (Mode B) Janos Lichtenberger
– 2nd International Workshop on Radio Methods for Studying Turbulence 2009, Warsaw, Poland A. W. Wernik (Mode B)
– The International Heliophysical Year (IHY) Africa 2009 workshop, Livingstone, Zambia, Lee-Anne McKinnell (Mode B)

8. Commission H Tutorial

Gordon James will give a tutorial at the next GA.
"Review of wave excitation, propagation, and detection, and new observation by E-POP satellite mission"

9. Discussion - Emerging Scientific Issues

9.1 Possible areas for new emphasis

New Frontiers
- Turbulence - Satellite constellations to measure wave properties
- Plasma waves at the planets
- Nonlinear waves in radiation belts
- Export knowledge to solar and astrophysical plasmas

Space Weather
- Satellites, man in space – particle acceleration and loss by waves

Ionosphere
- Canadian E-POP Satellite Mission and ground-based observation "Back-to-Ionosphere"
- Coupling of waves in the magnetosphere with the upper ionosphere
- Microwave interaction with the ionosphere regarding future SPS

Climate
- Particle precipitation by waves and atmospheric chemistry

Energy
- Solar power satellites – propagation and instabilities
- Fusion – wave heating of plasmas

Satellite propulsion
- Ion propulsion for space travel
- Plasma thrusters – wave acceleration, nonlinear wave-particle interaction

Measurement techniques of waves
- Calibration of electric field antenna

Ground observations
- Multiple ground observations as discussed at VERSIM workshop
- Encourage Long-term continuous monitoring in space and from the ground

Numerical simulations
- Simulation studies on inhomogeneous plasmas with massively parallel codes
- Combination of wave-particle interaction and wave propagation in 3D model

Database
- NASA's virtual wave observatory will be evolving over the next two to three years as the one website to go to for information about and access to wave data obtained around earth, other planets and the sun, with initial emphasis on IMAGE and Cluster data.
- Automatic event identification and derivation of electromagnetic plasma environment for huge wave data sets

10. Summary of raised problems

(1) Emerging new area: (session for next GA)
Plasma waves and ion thrusters

(2) Joint Working Groups
- a) HJE: "Supercomputing in space radio science" The title of the working group should be changed to the more general one: *"Computer simulations in space plasmas"*
- *b) ABDFGHJK: An inter-commission working Group on Solar Power Satellites:* Co-chair for Commission H: K. Hashimoto (Japan), Co-chair for Commission G: K. Schlegel.

(3) Joint Sessions: HBDGJK: Solar Power Satellites Com H. Kozo Hashimoto. The session is led by H, but the oral session should be taken as a separate session from Commission H time slots.

(4) Program Book: Identification of invited papers is necessary.

(5) Encouragement for young people: It is necessary to encourage young people to participate in the URSI GA. Since we only have a finite number of oral sessions, everyone should go to the poster sessions to discuss with young people.

BUSINESS TRANSACTED BY COMMISSION K

Chair : Dr. Frank Prato
Vice-Chair. Prof. G. D'Inzeo

Commission K Business Meetings were held on Monday 11 August 2008, Wednessday 13 August 2008 anf on Friday 15 August 2008

1. Welcome and Introductions

Dr. Frank Prato welcomed the national representatives and the observers.

2. Acceptance of Agenda

The agenda was accepted and it was agreed that at the Wednesday and Friday meetings agenda items will be added as needed.

3. Election of Commission K Vice Chair

Dr. Guglielmo D'Inzeo reviewed the guidelines for vice chairs and chairs. Then he introduced the two candidates for Vice Chair of Commission K. Then Dr. Masao Taki made a short presentation and that was followed by a presentation by Dr. Joe Wiart. Then after answering questions the vote was help. Dr. Prato announced that the election was extremely close but that Dr. Taki received a few votes more that Dr. Wiart.

4. Review and Update of Commission Terms of Reference

The following are the terms of reference for Commission K:

Commission K - ELECTROMAGNETICS IN BIOLOGY AND MEDICINE

The Commission is charged with promoting research and development in the following domains :
(a) Physical interaction of *electromagnetic fields** with biological systems;
(b) Biological effects of *electromagnetic fields*;
(c) Mechanisms underlying the effects of *electromagnetic fields*;
(d) Experimental *electromagnetic fields* exposure systems;
(e) Assessment of human exposure to *electromagnetic fields*;
(f) Medical applications of *electromagnetic fields*.
 * (*frequency range from static to terahertz*)

Proposal to replace:
* (*frequency range from static to terahertz*) with:
* (*frequency range from static to optical*)

Moved by Susan Hagness (US) and seconded by Rafi Korenstein (Isreal). After discussion the motion passed 11 to 4.

5. 2005 – 2008 Triennium Report

5.1 Contributions to the Radio Science Bulletin

5.1.1. Published Invited Reviews:

- Ahlbom, A., Feychting, M, and Lonn, S., 2005. Mobile Phones and Tumor Risk: Interpretation of Recent Results. *Radio Science Bulletin.* 314: 30-33.
- Lin, J. 2005. Interactions of Wireless Communication Fields with Blood-Brain Barrier of Laboratory Animals. *Radio Science Bulletin.* 315: 33-38.

5.1.2 Invited Reviews in Preparation

(Waiting for Guglielmo D'Inzeo email)

5.1.3 Radio – Frequency Radiation Safety and Health

- Lin, J. 2005. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin*. 315: 44-46.
- Lin, J. 2006. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin*. 316: 42-44
- Lin, J. 2006. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin*. 318: 67-68.
- Lin, J. 2006. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin.* 319: 67-68.
- Lin, J. 2007. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin.* 320: 48-49.
- Lin, J. 2007. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin.* 321: 54-55.
- Lin, J. 2007. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin.* 322: 41-42.
- Lin, J. 2008. Radio-Frequency Radiation Safety and Health. *Radio Science Bulletin.* 324: 41-42.

5.1.4 Published Commission K Tutorial Lecture

- Vecchia, P. 2006. Assessment of Health Affects Associated with Electromagnetic Fields by WHO, IARC, and ICNIRP. *Radio Science Bulletin*. 318: 30-33.

5.2 Sponsoring Scientific Meetings

The following scientific meetings received non-financial i.e. moral support from Commission K.

- International Symposium on Space THz Technologies (ISSTT), Paris, France, May 10-12, 2006
- International Conference on Ultrawideband, Waltham, MA, USA , September 24-27, 2006
- VIIth International Symposium on Electromagnetic Compatibility and Electromagnetic Ecology, St. Petersburg, Russia, June 26-29, 2007
- 2007 Asia-Pacific Microwave Conference, Bangkok,

Thailand, December 11-14, 2007
- ICMARS-2006, Jodhpur, India, December 20-22, 2006
- Millimeter Waves in Medicine and Biology, Moscow, Russia, April 2-5, 2007
- The Sixth International Kharkov Symposium on Physics and Engineering of Microwaves, Millimeter and Submillimeter Waves (MSMW'07), Kharkov, Ukraine, June 25-30, 2007
- Electromagnetic Compatibility EMC Europe 2008, Hamburg, Germany, September 8-12, 2008
- Microwave-08, Jaipur, India, November 2008
- 20th International Zurich Symposium on Electromagnetic Compatibility, Zurich, Switzerland, January 12-16, 2009
- Electromagnetic Compatibility – EMC-2009, St. Petersburg, Russia, 2009

5.3 International Symposium Held July 22-26, 2007, Ottawa, Canada

URSI International Commission K and CNC-URSI ran four symposia associated with the North American URSI Meeting in Ottawa, Canada, July 22-26, 2007 (see http://ursi2007.ee.umanitoba.ca/Home.html). Two were associated with Commission E CNC and US-NC. Three of the four sessions had an overarching theme: toward visualization of electromagnetic brain stimulation through electromagnetic brain imaging and mapping.

The first session (K2) focused on Neuronal Stimulation by both inductive and capacitive coupling including presentations on theory, simulations and/or experimentation. The third session (EK2) was a joint session on Electromagnetic Brain Imaging and Mapping with Commission E and focused on brain MRI, photo-acoustic imaging and current density imaging as well as brain mapping with EEG and electrical impedance tomography. The fourth session (K3) brought together the ideas in K2 and EK2 and covered Bioelectromagnetic Brain Imaging and Mapping of Effects from Electromagnetic Stimulation.

The second session was also with Commission E and this session (EK1) focused on breast imaging using microwaves - a very exciting, new and exploding field for URSI.

The success of these sessions allowed Commission K to decide on including similar sessions at the URSI GA08 in Chicago. These sessions especially the ones on Breast Imaging, Brain Imaging and imaging the effects of EMF brain stimulations have been oversubscribed suggesting that imaging will be a new large part of Commission K activities in the future.

The cost of this Symposium was about $40,000 CAN/USD. This was raised from the $8,000 EU available from URSI/Commission K, $5,000 CAN from a research grant from CIHR, $2,000 CAN for students from CNC/URSI and the remainder was generously provided by the Lawson Health Research Institute.

5.4 White Paper on Wireless Communication and Health

Dr. Bernard Veyret is preparing this white paper, requested by URSI. He has identified the authors for the different sections and will have a draft of the white paper soon after the general assembly in August 2008. The delay has been caused by the delay in the publications of the results from the interphone study.

5.5 Two Meetings of National Representatives of Commission K*

- June 12, 2006: A meeting was held in Cancun, Mexico at the 2006 Bioelectromagnetics Meeting.
- June 9, 2008: A meeting was held in San Diego, California at the 2008 Bioelectromagnetics Meeting.

* Minutes of these two meetings can be found at http://www.ursi.org/K/Index.htm

5.6 URSI Commission K Emerging Issues, Prepared by Bernard Veyret and Frank Prato

The driving issue behind the creation of Commission K was health risk assessment mainly related to mobile telephony. Since then, several emerging issues of heavy societal impact have been encompassed by the terms of reference for Commission K, especially in view of the still rapid development of wireless communication technologies and the emergence of the areas of "bioengineering" as a new area of emphasis at so many institutions, with new Departments of Bioengineering, Medical Imaging, Molecular Imaging and Molecular Biology being created. It is significant in this regard that the chair ship of Commission K has alternated between world leaders in risk assessment and biomedical engineering and imaging over the last 4 cycles.

While the underlying opportunities and applications in this connection are extremely broad, and cannot possibly be all addressed by URSI, or any other single organization, the relatively small but important component of the research thrusts of such departments, namely 'Electromagnetic Effects in Biology & Medicine' can be uniquely and most effectively captured by URSI.

The main emerging issues are today the new EMF-emitting devices (e.g., WiFi, Wimax, RFID) linked with dosimetric and standardization issues, and the biomedical applications of biomedical imaging (e.g., very high field MRI, microwave imaging, thermal imaging, near infrared imaging, optical imaging and hybrid imaging including optical/acoustic and microwave/acoustic), electrical mapping (e.g., electrical encephalography or EEG and electrical magneto encephalography or EMG) and electrical simulation (e.g., direct electrical stimulation and inductive non-invasive stimulation). It must be acknowledged in this regard that Commission K members must remain current in employing the latest in technology no matter where in the spectrum of these disciplines they work. For example they must use the latest in molecular biology regardless of whether research is in the traditional area of risk assessment (e.g. use of gene c-DNA arrays) or biomedical (e.g. developing reporter probes for molecular imaging).

Realization of such opportunities should be a new thrust of URSI, especially in view of their societal importance. In that context, significant interaction with other Commissions do exist already, namely commission A (e.g., field and SAR metrology), commission B (e.g., numerical methods and modeling of electromagnetic propagation in tissues, EM and statistics), commission E (e.g., development of EMI standards), commission F (e.g., terahertz propagation in tissue), and commission H (electromagnetics in conducting media).

In order to strengthen its role in health risk assessment and standard setting, commission K has built strong links with WHO and ICNIRP.[1]

Hence Commission K has two important roles to play within URSI. The risk assessment role is that of "hand maiden" to the other commissions where, for example, Commission K members use the latest tools to test for safely of a new wireless technology. The second role is where Commission K leads and asks other commissions to lend their expertise to develop new technologies such as the understanding of EM field transmission characteristics for microwave breast imaging. It is this second role that has the capacity of explosive growth but it is also the area most likely to be taken over once it reaches a level of commercialization for medical application by large well funded medical imaging societies. However Commission K can achieve a novel niche by leveraging the strengths of the other URSI commissions.

5.7 Preparations for GA08, August 9-15, 2008, Chicago

Commission K will lead in 11 specific sessions and one poster session. This includes one session with Commissions B and E on microwave breast imaging and one with commissions A and E on exposure assessment of new emerging technologies. Commission K has combined with Commission B on a session with the title "Future Challenges of Computational Electromagnetics" and with Commission B and F with the title "Stochastic Modeling and Uncertainty Arrangement in Electromagnetics". All 13 of these oral sessions have been filled and in addition there are a total of 31 posters and 1 Commission K Tutorial on Wireless Communication and Health. Hence there are a total of 134 Commission K presentations with 31 of these being posters.

5.8 Nomination of Dr. Shoogo Ueno for the Balthasar Van der Pol Gold Medal of URSI Society

Dr. Shoogo Ueno was nominated for a Gold Medal of the URSI Society. Although Dr. Ueno was more than deserving for an extensive career in research, teaching and administration his nomination, through no fault of his own, was not successful. Dr. Ueno has served our community unselfishly as a former Chair of Commission K and President of BEMS. Although not successful, Commission K members would like Dr. Shoogo Ueno to realize that his associates and colleagues hold him in the greatest regard.

5.9 Student Support at URSI

Commission K had $5,000 US for student support and decided to use it to offset student travel costs by giving $300 US to each of the 16 students. Three Commission K students received Young Scientific Awards.

One Commission K student's manuscript was selected in the 10 finalists for the URSI student paper competition.

6. Commission K RSB Associate Editor for the next Triennium – Dr Guglielmo D'Inzeo

Dr. Guglielmo D'Inzeo proposed that Dr. Joe Wiart become the Associate Editor of the Radio Science Bulletin for Commission K. This motion was seconded by Dr. Frank Prato and was unanimously approved by the National representatives.

7. Emerging Issues and GA11 – Dr. Guglielmo D'Inzeo

Dr. Guglielmo D'Inzeo proposed that the issues for the next GA in 2011 would be discussed through out the next triennium.

8. Other Business

8.1 Proposed Resolutions

Dr. Frank Prato read over the proposed resolutions being considered by the URSI council this included the WG on Catastrophes and Disasters, the establishment of regional committees at the same location as those to be set up by ICSU, the reduction in the distribution of paper copied of the RSB and the change of GA11 name to GA11 and Scientific Symposium or GASS.

8.2 Long Range Planning Committee

Dr. Frank Prato indicated that the board has suggested that there by a Long Range Planning Committee to be made up of immediate past commission chairs.

8.3 Location of 2011 meeting: Beijing, Goteborg, Istanbul

The location of the 2011 meeting was discussed. Preference for location was voted on as suggested by Dr. Neils Kuster (Switzerland). The vote was Istanbul – 1 vote, Goteborg – 12 votes and Beijing – 2 votes. At the next council meeting Istanbul won the election.

8.4 2010 Asia-Pacific RS Conference in Toyama, Japan

Frank Prato quickly reviewed the Japanese proposal for the Asia-Pacific Radio Science Conference in Toyama Japan.

8.5 Continuation of the Inter-Commission Working Group on Solar Power Satellites

As requested by Commission H chair Kozo Hashimoto there was a discussion of continuation of the SPS ICWG and the inter commission session on SPS. It was decided that Dr. Guglielmo D'Inzeo would ask Dr. James Lin if he would continue to serve as commission K's representative on this Working Group.

8.6 Proposal for White Paper on Remote Sensing

There was a discussion on the French proposal to have a white paper on Remote Sensing. Dr. Joe Wiart proposed that Commission K should have input into the first draft and Dr. Guglielmo D'Inzeo will appoint some one.

8.7 Proposal from Commission A Chair P. Banerjee to have a A,K,C combined session at the GA11 on "EMF Exposure and Health".

Dr. Guglielmo D'Inzeo will contact Dr. Banerjee on this proposal

[1] International Commission on Non-Ionizing Radiation Protection

UNION RESOLUTIONS & RECOMMENDATIONS ADOPTED AT THE MAASTRICHT GA

U.1 Working Group on Natural and Human-Induced Hazards and Disasters

The URSI Council,

considering
1. the multidisciplinary approach adopted by ICSU for its program on "Natural and Human-Induced Environmental Hazards and Disasters";
2. URSI competences in the development of models and tools in earth observation and remote sensing of the environment as well as the use of global data bases for various applications;
3. the importance of the evaluation and management of risk (linked, for example, to climate change), particularly in developing countries;
4. opportunities of interaction and collaboration with committees from other Unions (ITU, GEO, ISRPS), and Interdisciplinary Bodies (COSPAR);

resolves
1. to create an Inter-Commission Working Group, the main objectives of which shall be:
   a. to study, within the URSI area of competence, methods and strategies related to natural and human-induced environmental hazards and disasters, such as:
      (i) communication systems suitable for fast-response disasters relief;
      (ii) the development and application of remote sensing products and other global data for monitoring and alerting;
      (iii) the evaluation of long-term and short-term risks of disasters, and
      (iiii) the description of the environment disturbances resulting from disasters;
   b. to provide support to initiatives taken in the area of risk management and relief related to natural and human-induced catastrophes and disasters, particularly by developing countries.

U.1. Groupe de travail sur les risques et catastrophes, naturels ou dus aux activités humaines

Le Conseil de l'URSI,

considérant
1. l'approche multidisciplinaire adoptée par l'ICSU pour son programme sur les « risques environnementaux et catastrophes qu'ils soient naturels ou dus aux activités humaines » ;
2. les compétences de l'URSI dans l'élaboration de modèles et d'outils en l'observation de la terre et télédétection de l'environnement ainsi que dans l'utilisation de bases de données globales ceci pour des applications diverses;
3. l'importance de l'évaluation et de la gestion des risques (liés, par exemple, aux changements climatiques), en particulier dans les pays en développement;
4. les possibilités d'interactions et de collaborations avec des comités d'autres unions (UIT, GEO, ISRPS) et de structures interdisciplinaires (COSPAR);

décide

1. de créer un groupe de travail inter-commissions, dont les principaux objectifs devront être :
   a) d'étudier, dans les domaines de compétence de l'URSI, des méthodes et stratégies relatives aux risques environnementaux et catastrophes qu'ils soient naturels ou dus aux activités humaines, tels que:
      (a) des systèmes de communication adaptés à une réaction rapide des secours aux catastrophes;
      (b) l'élaboration et l'application des moyens de la télédétection, et autres données globales, au suivi et l'alerte;
      (c) l'évaluation à long terme et à court terme des risques de catastrophes, et
      (d) la description des perturbations de l'environnement résultant de catastrophes;
   b) de fournir un appui aux initiatives prises dans le domaine de la gestion des risques et des secours liés aux risques et catastrophes qu'ils soient naturels ou dus aux activités humaines, en particulier aux pays en développement.

U.2. Regional Network Committees

The URSI Council,

considering
1) the need to involve more countries in radio science;
2) the new opportunities opened by the ICSU Regional Centres;
3) the need to adopt different approaches for different regions;
4) the need to establish clear collaborative structures from the regional URSI members and the Board;

resolves
1) to dissolve the URSI Standing Committee for Developing Countries;
2) to create Regional URSI Networks, including those covering the same geographical regions as the ICSU Regional Centres (presently Africa, Latin America & the Caribbean, Asia-Pacific),
3) to constitute Regional URSI Network Committees based on agreement between the regional URSI members and the Board;
4) that each Regional URSI Networks be assisted and supervised by an URSI Board member;
5) to have as a first objective the formation of action plans, including actions associated with the corresponding ICSU Regional Centre;
6) to use the opportunity of URSI General Assemblies to hold meetings with the URSI Board members and with other Union Members involved in similar action plans.

U.2. Comités réseaux régionaux

Le Conseil de l'URSI,

considérant

1) la nécessité d'impliquer davantage de pays dans les radio sciences ;
2) les nouvelles possibilités offertes par les centres régionaux de l'ICSU ;
3) la nécessité d'adopter des approches différentes par régions ;
4) la nécessité de définir des structures de collaboration claires prenant appui sur les membres régionaux de l'URSI et le Bureau ;

décide

1) de dissoudre le Comité permanent de l'URSI pour les pays en développement;
2) de créer des Réseaux régionaux de l'URSI, comprenant ceux couvrant la même région géographique que les centres régionaux de l'ICSU (actuellement l'Afrique, l'Amérique latine et les Caraïbes, et l'Asie - Pacifique) ;
3) de constituer les Réseaux régionaux de l'URSI sur la base d'accords entre les membres régionaux de l'URSI et le Bureau ;
4) que chaque Réseau régional de l'URSI soit assisté et supervisé par un membre du Bureau de l'URSI :
5) d'avoir pour premier objectif la définition de plans d'action, prenant en compte les actions associées avec les centres régionaux de l'ICSU ;
6) d'utiliser les possibilités offertes par les Assemblées générales de l'URSI pour tenir des réunions entre les membres du Bureau de l'URSI et des membres d'autres Unions engagées dans des plans d'action analogues.

U.3. Inter-Commission Working Group on Radio Science Services

The URSI Council,

recognizing
1) the fast development of new communication systems and their potential consequences for passive and active radio science services;
2) the leadership taken by IUCAF (the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science) for the protection of passive radio science services;
3) the involvement of URSI in the study and development of new communication systems and the importance of passive and active radio services for several URSI Commissions;
4) the interactions to be developed with ITU and with other Unions (ISPRS) and organizations (GEO, IEEE, …) on the use of passive and active radio services;

resolves

1) that an inter-Commission WG on Radio Science Services (RSS) be established, having as its mission:
2) in close relation with IUCAF, to provide URSI input to the ITU on all matters that may concern passive as well as active radio services;
3) to inform the URSI Commissions regarding the development of new communication systems, and to study with them the potential consequences for radio science research;
4) to contribute to inter-Union and/or inter-Organization activities related to passive and active radio services.

U.3. Groupe de travail inter-Commission sur les services radio scientifiques

Le Conseil de l'URSI,

reconnaissant

1. le développement rapide de nouveaux systèmes de communication et leurs conséquences potentielles pour les services radio scientifiques actifs et passifs;
2. le leadership pris par l'IUCAF (le comité scientifique sur l'attribution des fréquences pour la radio astronomie et les sciences spatiales) pour la protection des services radio scientifiques passifs ;
3. la participation de l'URSI dans l'étude et le développement de nouveaux systèmes de communication et l'importance pour plusieurs commissions l'URSI des services radio actifs et passifs
4. les relations à développer avec l'UIT et autres unions (ISPRS) ou organisations (GEO, IEEE,...) sur l'utilisation des services de radio actifs et passifs;

décide

qu'un groupe de travail inter-commission sur les Services Radio Science (SRS) soit établi, ayant pour mission :
1) en étroite collaboration avec l'IUCAF, de fournir des informations et données à l'UIT sur tout sujet qui peut concerner tant les services radio actifs que passifs ;
2) d'informer les commissions de l'URSI en ce qui concerne le développement de nouveaux systèmes de communication, et d'étudier avec elles les conséquences potentielles pour la recherche en radio science;
3) de contribuer aux activités inter-unions ou inter-organisations relatifs aux services radio actifs et passifs.

U.4. Distribution of "*The Radio Science Bulletin*"

The URSI Council,

Considering

1) that *The Radio Science Bulletin* (published quarterly in March, June, September and December) is an important information channel for the radio science community;
2) that all issues of *The Radio Science Bulletin* have been posted on the URSI Website since September 2002;
3) that the printing and mailing of *The Radio Science Bulletin* is a major cost for URSI;

resolves

that from the March 2009 issue of *The Radio Science Bulletin* onwards:
a) URSI Radioscientists and Officers no longer receive a gratis paper copy of *The Radio Science Bulletin;*
b) a limited number of issues will be sent in bulk mailing to the academies (4 copies per dues category) (which ranges from 1 to 6), with a minimum of 10;
c) there will be only one such mailing per Member Committee;
d) those who wish to receive a printed version of *The Radio Science Bulletin* will need to pay a subscription fee of 100 euros per triennium (or 60 euros in addition to the registration fee for the General Assembly);
e) libraries will be able to take a subscription at the rate of 100 euros per year.

U.4. Distribution du «Radio Science Bulletin»

Le Conseil de l'URSI,

considérant

1) que le Radio Science Bulletin (revue trimestrielle publiée en mars, juin, septembre et décembre) est un important canal d'information pour la communauté radio scientifique;
2) que tous les numéros du Radio Science Bulletin ont été publiés sur le site depuis l'URSI septembre 2002 ;
3) que l'impression et l'envoi du Radio Science Bulletin représente un coût important pour l'URSI;

décide

que, dès le mois de mars 2009 les numéros du Radio Science Bulletin :
1) les radioscientifiques et les dirigeants de l'URSI ne recevront plus gratuitement une copie papier du Radio Science Bulletin ;
2) un nombre limité de numéros sera adressé groupé aux académies 4 exemplaires par catégories de cotisations (lesquelles vont de 1 à 6), avec un minimum de 10 ;
3) il n'y aura plus qu'un envoi postal par membre ;

Ceux qui souhaitent recevoir une version imprimée du Radio Science Bulletin devront payer un abonnement de 100 euros par période triennale (ou 60 euros en plus des frais d'inscription pour l'assemblée générale);

Les bibliothèques pourront s'abonner au taux de 100 euros par an.

U.5. Visibility of URSI General Assemblies by scientists and medias

The URSI Council,

considering

that the General Assembly of URSI is much more than the General Assembly of one major scientific union; that it is also a great scientific symposium covering the whole spectrum of radio sciences;

resolves

that its title be changed to: "URSI General Assembly and Scientific Symposium".

U.5. Visibilité des Assemblées générales de l'URSI par les scientifiques et les médias

Le conseil de l'URSI

considérant

que l'Assemblée générale de l'URSI est bien plus que l'Assemblée générale d'une des grandes unions scientifiques, qu'elle est aussi un grand symposium scientifique couvrant tout le spectre des radio sciences ;

décide

que son intitulé soit changé en : « Assemblée générale et Symposium scientifique de l'URSI »

U.6. Formation of an Inter-Commission Data Committee

Considering

1. That ICSU (International Council for Science), through its recent SCID (Strategic Committee on Information and Data) will recommend to the ICSU General Assembly that a new Interdisciplinary Body is formed, called WDS (World Data Systems), that FAGS (Federation of Astronomical and Geophysical Data analysis Services), WDC (World Data Centre) will no longer exist and the current FAGS Services and World Data Centres applying for membership of the WDS;
2. That URSI currently has representatives for the WDC, the FAGS, and ISES (International Space Environment Services), a FAGS Service;
3. That through the SCID report, ICSU has proposed all Unions and National bodies to form committees to deal with data and information;
4. That all URSI Commissions have varied data needs and interests, which are expected to grow in complexity and importance;

Resolves

1) That URSI form an inter-Commission Data Committee;
   a) to provide an oversight of URSI data interests;
   b) to provide an effective interface with other ICSU data communities, including over-arching groups such as GEOSS (Global Earth Observing System of Systems), the proposed WDS and the **Committee on Data for Science and Technology** (CODATA), which URSI recently joined;
2) That the initial membership include the current WDC, FAGS and ISES representatives, together with representatives proposed by the Commissions;
3) That the Data Committee provide regular reports to the URSI Board and Council and respond to questions from the Commissions, the Board and Council;
4) That the Data Committee develop its own terms of reference and propose these to the Board for further development prior to the next General Assembly, in 2011.

U.6. Comité inter-commission sur les données

Considérant

1. que l'ICSU (Conseil international pour la science), par l'intermédiaire de son récent SCID (Comité stratégique sur l'information et les données) recommandera à l'Assemblée générale du ICSU qu'une nouvelle structure interdisciplinaire soit formée, appelé WDS (World Data Systems), que la FAGS (Federation of Astronomical and Geophysical Data analysis Services) et le WDC (World Data Centre) soit supprimés, et que les actuels services FAGS et les centres mondiaux de données soit candidats aux WDS;
2. que l'URSI a actuellement des représentants au WDC, à la FAGS, et à l'ISES (International Space Environment Service), un service de la FAGS;
3. qu'avec le rapport SCID, l'ICUS a proposé à toutes les unions et les structures nationales de former des comités pour traiter des données et de l'information ;
4. que toutes les commissions de l'URSI ont, s'agissant de données diverses, des besoins et intérêts, qui sont appelés à croître en complexité et importance ;

Décide

1) que l'URSI forme un Comité inter-commission sur les données :

a) manifestant l'intérêt de l'URSI pour les données ;
b) permettant une interface efficace avec d'autres communautés de données de l'ICSU, y compris des groupes plus globaux tels que le GEOSS (Global Earth Observation System of Systems), le projet de WDS, et le Comité sur les données pour la science et la technologie (CODATA), que l'URSI à récemment rejoint ;

2) que les premiers membres soient les représentants actuels au WDC, à la FAGS et à l'ISES ainsi que des représentants proposés par les commissions;
3) que le Comité sur les données présente des rapports réguliers au Conseil et au Bureau de l'URSI et réponde aux demandes des Commissions, du Bureau et du Conseil
4) que le Comité sur les données élabore ses propres termes de référence et les propose au Bureau pour une mise en oeuvre avant la prochaine Assemblée générale, en 2011.

U.7. Radio Science and the Square Kilometre Array

The URSI Council,

considering

1. The Square Kilometre Array (SKA) will be the next generation radio telescope operating at cm – and m-wavelengths;
2. the unprecedented potential of the SKA for transformational radio science and technology;
3. the coordinated global development of the SKA; and
4. the involvement in the Square Kilometre Array programme by the international community of Radio Scientists represented by URSI;

recommends

that URSI, through its Commissions, fosters the scientific and technical development of the SKA through its meetings, publications and other means.

U.7. Radio science et la Square Kilometer Array (SKA)

Le Conseil de l'URSI,

considérant

1. que la Square Kilometer Array (SKA), sera la prochaine génération de radio télescope opérant dans les longueurs d'onde centimétrique et métrique;
2. le potentiel sans précédent de la SKA pour l'évolution des sciences et technologies radio;
3. la coordination mondiale du développement de la SKA, et
4. la participation dans le programme « Square Kilometer Array » de la communauté internationale Radio scientifiques représentées par l'URSI;

recommande

que l'URSI, par l'intermédiaire de ses commissions, favorise le développement scientifique et technique de la SKA par le biais de ses réunions, publications et de tout autres moyens.

U.8 XXXth General Assembly 2011

The URSI Council,
Having considered the invitations for the XXXth General Assembly which had been submitted by the URSI Member Committees in China CIE (Beijing), Sweden (Göteborg) and Turkey (Istanbul);

resolves

1. to accept the invitation of the Turkish URSI Committee to hold the XXXth General Assembly in Istanbul from 13 to 20 August 2011;
2. to record its thanks to the Member Committees in China CIE and in Sweden for their invitations.

U.8 XXXe Assemblée Générale 2011

Le Conseil de l'URSI,

Ayant examiné les invitations pour la XXXe Assemblée générale soumises par les comités membres de l'URSI en Chine (Beijing), la Suède (Göteborg), et la Turquie (Istanbul);

Décide

1. d'accepter l'invitation du comité turc de l'URSI pour organiser la XXXe Assemblée générale à Istanbul du 13 à 20 août 2011;
2. d'adresser aux comités membres en Chine et en Suède ses remerciements pour leurs invitations.

U.9 Vote of Thanks to the US URSI Committee

The URSI Council,

resolves unanimously to convey to the US URSI Committee its warm thanks and appreciation for the organisation of the XXIXth General Assembly in Chicago.

U.9 Remerciements au Comité américain de l'URSI

Le Conseil de l'URSI,

décide à l'unanimité de transmettre au comité américain ses vifs remerciements et son appréciation pour l'organisation de la XXIXe Assemblée générale à Chicago.

Conferences

CONFERENCE REPORTS

2008 Radiation Belts - RBSPb Workshop

St. Petersburg, Russia, 4 - 6 August 2008

Motivation and Venue

Earth's radiation belts, zones of extremely energetic particles encircling the planet in space, were discovered in 1958 by the Explorer I team led by James Van Allen. Some five decades later, many puzzles remain to be solved about how these particles are accelerated to high energies or scattered (lost) into the upper atmosphere. The recent Radiation Belts, Saint Petersburg (RBSPb) workshop was held in Russia on 4-6 August 2008 to explore ways to make scientific progress on this topic.

Format and Philosophy

The RBSPb workshop was small (a dozen attendees), attended by invitation only, and the atmosphere was informal. As this was the first meeting of its kind, the meeting conveners experimented with formats that would strongly encourage questions, arriving at the following formula. Speakers chose either a brief talk with questions at the end (appropriate for short presentations on future missions, etc.) or a much longer presentation in which speakers could be interrupted with any question. Several speakers' talks were interrupted by an audience member getting up to give a relevant tutorial that would elucidate a point or answer another participant's question. To facilitate such tutorials and generally encourage spontaneity, a large notepad was posted at the front of the room for participants to sketch diagrams. A free-flowing logical discussion, rather than the formal 20-minute talks found at bigger meetings fostered an atmosphere of questioning and mutual learning among participants.

Global System Controlled by Local Processes

All the presentations and discussions at the RBSPb workshop reflected the consensus view that resonant interactions with various plasma waves—Alfven and magnetosonic waves, whistler mode chorus, hiss, lightning generated whistlers, anthropogenic whistlers, and electromagnetic ion cyclotron (EMIC)—exert a major controlling influence upon the dynamics of energetic electrons in the radiation belts. This view is nicely captured by a statement made at the workshop: the radiation belts are a global system governed by local processes. Excitation and non-linear growth of waves in turn depend on both the global and local properties of the inner magnetosphere which in turn is largely driven by the solar wind. The RBSPb participants therefore agreed that producing an accurate characterization of energetic electrons will require dynamic, multi-scale quantification of the contributions from all the various waves. This is the task facing the geospace community today, and accomplishing it will require using observation side by side with theory. Important topics raised at RBSPb for further development include inclusion of nonlinear wave growth and scattering algorithms, establishment of community-accepted standards and practices for testing the predictions of models against observations, and more widespread understanding of the intimate details of wave resonance calculations.

The picture described above is of course incomplete. Other processes besides wave-particle interactions also may contribute to energization or loss of electrons: shocks (particularly important for multi-MeV electron acceleration), loss of electrons that encounter the magnetopause boundary and escape the trapping region, and Coulomb scattering (which can become dominant in the inner electron belt). The process of charge exchange can deplete the population of the proton radiation belt.

Observing and Modeling the Radiation Belts

A single satellite's in situ measurement is by definition restricted to a single point in space at any given time, which complicates analysis of the outer radiation belt which evolves on the time-scales ranging from minutes to years. Wave measurements from a single spacecraft also cannot generally be used to infer the global spatial distribution of waves. An exciting topic at the RBSPb workshop was therefore the prospect of several currently-planned missions, including NASA's Radiation Belt Storm Probes (RBSP) and Balloon Array for Radiation-Belt Relativistic Electron Losses (BARREL), Canada's Outer Radiation Belt Injection, Transport, Acceleration, and Loss Satellite (ORBITALS), Russia's Resonance, and Japan's Energization and Radiation in Geospace (ERG). These missions are all slated for launch in or near 2012, which would provide increased spatial coverage during individual events that could help disentangle spatial from temporal features, and local from global processes. In the event that programmatic issues prevent simultaneous missions, sequential missions would provide continuous coverage in time, yielding better statistics on long term characteristics. Either way, these missions are good news for radiation belt science. As an added bonus, the currently-flying multi-spacecraft Time History of Events and Macroscale Interactions During Substorms (THEMIS) mission is capable of providing extremely useful measurements of EMIC, chorus, and hiss waves.

With all opportunities come challenges. At the RBSPb workshop, much discussion took place regarding how to yield the most scientific benefit from data, with a twofold purpose. First, it is important to apply new analysis tools and updated ideas to existing datasets, which will further advance our ideas. Second, the community ideally should develop concepts, data analysis, and intra-community collaboration skills prior to the launch of the expected future missions. With these goals in mind, the RBSPb workshop explored taking a fresh look at electron decay rates measured by older missions like Spacecraft Charging at High Altitude (SCATHA), and applying newer insights about the global aspects of radiation belt physics, such as the influence of the global distribution of cold dense plasma upon wave-particle interactions. Recently developed techniques were reported at RBSPb, such as the ability to gain quantitative information from electron-contaminated proton detectors, and the use of auroral imaging to estimate EMIC wave scattering of ring current ions. Fruitful use of these techniques will rely upon proper understanding of the theory of relativistic electron scattering by waves. For example, impromptu tutorials presented the relationship between wave dispersion properties and resonance conditions, and some of the details of normal mode analysis.

Future instrument development was also discussed at RBSPb, motivated by the need to design instruments that provide the measurements needed by theorists to answer the truly important outstanding questions. One problem discussed at length: the radiation belt community needs to improve communication between theorists and observationalists. Theorists in principle can help improve instrument design by providing key input during instrument design. In turn, experimentalists can help teach theorists how to use data properly, and can provide better documentation of the quirks of particular datasets. Options explored to promote this communication included special sessions at meetings and encouraging instrument experts to write review papers on appropriate data analysis topics.

What's Next?

At the end of the workshop, a planning session was held at which several conclusions were reached by consensus. First, future RBSPb workshops (and perhaps sessions at other meetings) should adopt the format and philosophy of the 2008 meeting, which favored questioning and learning over formal presentations. It was agreed that such adoption would necessitate small workshops (no more than 20 attendees). Second, stronger links should be forged among instrumentation designers, observationalists, and theorists. The RBSPb conveners established a website where information about collaborations and future workshop information would reside, online at http://enarc.space.swri.edu/RBSPb/.

Acknowledgements

The RBSPb conveners sincerely thank the workshop attendees for a truly enjoyable and successful meeting, and express their gratitude to the International Union of Radio Science (URSI) for making the meeting possible with truly generous financial support.

3rd VERSIM Workshop 2008
ELF/VLF Radio Phenomena: Generation, Propagation and Consequences in Observations, Theory and Modelling

Tihany, Hungary, 15 - 20 September 2008

Overview

The 3rd VERSIM Workshop took place in September 2008 at the Balaton Limnological Research Institute (BLRI) of Hungarian Academy of Sciences, sponsored by Eötvös University and supported by IAGA and URSI Commission G and 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 slightly more than 50 participants from 15 countries, ranging from India and Serbia all the way to Brazil and the USA, and included 61 presentations. Due to the increased number of presentations the workshop length was increased by one day, to maintain the established structure of the timetable; oral presentations to of a sensible length (~20-30 min), interspersed by good-length coffee and lunch breaks in which participants could follow up with more detailed discussions, or plan future scientific collaborations.

The 3rd workshop builds on the success on the previous 2 meetings, which were held in Sodankylä, Finland.

With steadily more participants and more presentations at each VERSIM workshop, it is clear that the workshops are filling an important role for the VERSIM community. Many of the participants at the 3rd workshop commented that the quality of the talks had steadily improved with each VERSIM workshop, suggesting that the collaborations established through VERSIM workshops were leading to rapid forward motion in VERSIM-Science. Participants at the 3rd workshop agreed that the success of this workshop confirms the viability of recurring VERSIM workshop as part of our future scientific calendars.

Many past VERSIM chairs were present at the 3rd workshop, including Don Carpenter (Stanford University, USA) who was the first chair of the *Whistlers in the Magnetosphere URSI* joint committee. This evolved into the current joint URSI-IAGA VERSIM working group. During the business meeting at the end of the workshop the current chairs paid tribute to all the previous VERSIM working group chairs, most of whom are still active members of the VERSIM community.

The 3rd VERSIM workshop was marked by a significant series of talks on the use of VLF and ULF waves to provide plasmaspheric parameters, both electron density and mass density, which when combined allow ground-based observations of plasmasphere composition. Some VERSIM researchers are rapidly moving towards automated detection and analysis of VLF whistlers and ULF-field line resonances, which should provide near-continuous ground-based plasmaspheric measurements from multiple stations. Combined with the power of the internet, near-realtime reporting of plasmaspheric parameters should be possible in the near future. This is a highly promising development, linking to the earliest goals of the working group (and its predecessors), made possible by recent improvements in technology and growing scientific understanding. At the same time, these studies have pointed to gaps in our knowledge as to detailed route by which ground-based VLF sources couple into space, for example the VLF radiated by a lightning discharge creating whistlers. Several reports focused on the finer details of this coupling, through ray-tracing and entirely experimental measurements. In addition, multiple papers dealt with the interaction between waves and energetic electrons in the radiation belts, both as a mechanism for affecting the waves, or the particles (acting as an acceleration or loss process). One set of invited talks at the 3rd VERSIM workshop offered homage to workers in our field over more than 4 decades of research, providing context for our current efforts. Another invited talk focused on high-end experimental observations, where 1 days wideband ground-based recording and analysis leads to many hundreds of gigabytes of data, with a noise floor of 100 $aT/Hz^{-1/2}$. A very common feature throughout the workshop was the use of observations from the Centre National d'Etudes Spatiales (CNES) DEMETER spacecraft. The launch of DEMETER was reported at the first VERSIM meeting in September 2004, and has made such an impact on the community that roughly 50% of the presentations made use of DEMETER data. A full listing of the abstracts presented at the 3rd VERSIM workshop can be found at: http://sas2.elte.hu/versim/versim1.htm

The support from URSI, IAGA and local sources was used

- to support the participation of 9 young scientists from Hungary, New Zealand, South Africa and USA with waived registration fee and free accommodation,
- to support the participation of 3 scientists from disadvantaged nation (India, Russia and Slovakia) with waived registration fee and/or free accommodation,
- to cover the air fares of 2 invited scientist (Don Carpenter, Stanford University, USA and Tauno Turunen, SGO, Finland)

As part of the IAGA support for the 3RD 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 (Sopron, Hungary in 2009): a low-cost air ticket, waiving of the registration fee, and USD 200 as a contribution to cover hotel and subsistence costs. The Scientific Committee of the 3rd VERSIM Workshop proposed Mr. Mark Golkowski for the IAGA Young Scientist Presentation Award. Mr. Golkowski is a PhD Student at Stanford University (USA). His presentation focused upon ELF/VLF triggered emissions generated by the High Frequency Active Auroral Research Program (HAARP) facility in Alaska. The ELF/VLF wave generation by heated modulation of the ionospheric auroral electrojet currents allow controlled magnetospheric wave injection experiments. The HAARP facility has been used to inject ELF/VLF waves into the magnetosphere to trigger wave-particle interactions that result in the non-linear amplification of the wave. Amplified and triggered waves are observed on the ground at both ends of the magnetic field line and also on the DEMETER satellite. Ground-based observations in the conjugate region came from an ELF/VLF receiver onboard a buoy tethered in the South Pacific in an ocean many kilometres deep! The combination of multiple receiving sites with the HAARP facility provided new understanding into the production and propagation of these emissions, and was delivered in a highly polished manner. Well done Mark!

Some idea of the success of this session can be found on the Photos page of the 3rd VERSIM Workshop 2008: *http://sas2.elte.hu/versim/photos*

Future

On the basis of discussions which took place during the 3rd workshop, our colleagues from the Czech Republic have offered to host the next workshop in Prague. It was felt that the time in which VERSIM workshops are currently taking place leaves a sensible gap between URSI/IAGA meetings and the VERSIM workshops, and hence that the 4th workshop will occur sometime in September 2010, possibly in the first week of that month. Our Czech colleagues will contact the community with some possible dates. The meeting strongly endorsed this plan, and thanked our Czech colleagues for taking this task on.

Craig J. Rodger and János Lichtenberger
VERSIM Working Group Chairs

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 an excursion and reception on Lake Balaton, onboard the Steamboat Kelén, built in 1891 and the oldest vessel on the lake. The excursion was followed by a concert of traditional Hungarian folk music, performed by the Muzsikás Ensemble. This was a special present to the 3rd Workshop from the conference organisers, and was particularly fitting given that one of the Ensemble, Dániel Hamar is an active researcher inside the VERSIM community! During the concert our Hungarian colleges provided samples of Hungarian "Palinka", made by the chair of the Local Organising Committee, János Lichtenberger. Muzsikás has previously played in famous concert venues across the world, and are the winner of the 2008 WOMEX Award, but during the 3rd VERSIM workshop they entertained the participants with a special dedicated concert. This is likely to be the longest lasting memory of the workshop for many of the participants, despite the high quality scientific presentations which occurred during the day. The Workshop hosts also arranged wine tasting, a visit to a monastery founded 953 years ago, meals, rounded off with a medieval evening in Sümeg castle during which one of the participants was "knighted". The participants and accompanying people were thoroughly looked after by the meeting hosts. I'd would like to point out that the levels of Hungarian hospitality we experienced bodes well for the next IAGA General Assembly, to be held in Sopron (Hungary) in August 2009!

Craig J. Rodger

Some photos

Mark Golkowski (on left in foreground), winner of the IAGA Young Scientist Presentation Award, at the conference dinner.

*Looking back towards Tihany during the VERSIM excursion onboard the Steamboat **Kelén.***

The 3rd VERSIM Workshop, group photo outside the Balaton Limnological Research Institute building.

International School on Atmosphere-Ionosphere Remote Sounding and Modelling ISAR-NCU 2008 and Sustainable Development Forum

Chung-Li, Taiwan, 6 - 17 October 2008

This school, introduced by the forum, was the third one held at the National Central University (NCU) in Chung-Li, Taiwan, following the first two in October 2006 and October 2007, respectively. The structure and content of ISAR-NCU-2008 was somewhat changed as compared to the earlier schools to widen the scope on active and passive methods for studies of the atmosphere and ionosphere with radio waves. All the school and related activities were held 6 - 17 October 2008 at the Center for Space and Remote Sensing Research (CSRSR) on the campus of NCU.

The school followed a one-day Forum on Sustainable Development, which was conducted by NCU on 6 October 2008 to honor the accomplishments of Prof. Chao-Han Liu, former president of NCU and vice president of the Academia Sinica Taiwan. Besides presentations by honorable Taiwanese speakers on a wide variety of educational topics and scientific projects there were the following presentations by speakers from the international community: Charles L. Rino, USA, on "Scintillation from 1965 to 1990 as historical sketch to honor C.H. Liu", Jürgen Röttger, Germany, on "The early decades of ionospheric and atmospheric radar science and the impact of the NCU VHF radar in Chung Li", Vyncheslav Kunitsyn, Russia, on "Ionospheric tomography: Beginning and development", and by W.K. Kuo, NCAR USA, on "The FormoSat-3/COSMIC mission: Scientific results and impacts".

These speeches, which all related to the syllabus of the following school ISAR-NCU as well, covered the main directions of Prof. C.H. Liu's science career. This first day was closed by a banquet in Taipei to which the main speakers and other honorables were invited by Prof. Liu, who was also honored on his 70th birthday and by the edition on the same day of a book digesting his time at NCU.

The following morning on 7 October 2008 the school ISAR-NCU-2008 was formally opened by the Acting President of the National Central University, Prof. Wei-Ling Chiang, in the presence of Prof. C.H. Liu, the vice president of NCU Prof. Wing Ip, the director of CSRSR, Prof. Y.A. Liou, and minister of the National Science Council Prof. Lu-Chuang Lee as well as other distinguished representatives of NCU. During the opening ceremony Jürgen Röttger presented a short introduction of the forthcoming school lectures and a summary of the historical development of the International Schools on Atmospheric Radar, which started in 1988 by the Radio Atmosphere Science Center of the Kyoto University in Japan. With this school held in 2008 at NCU the twenty-years anniversary was celebrated and it was resolved to dedicate ISAR-NCU-2008 to Prof. Chao-Han Liu, former president of NCU and mentor and tutor of atmospheric and ionospheric radio science.

To commence the school a workshop was held on this day, which began with a presentation of C.H. Liu on "An overview of radio science and space programs in Taiwan" followed by topical speeches by S. Fukao, Japan, on "Recent advances in atmospheric radar studies" and by W.K. Kuo, USA/Taiwan, on "Applications of FormoSat-3/ COSMIC to weather". These were then followed by presentations by V.E. Kunitsyn and E.S. Andreeva, Russia, on "Tomography", and by local speakers Y.H. Chu on "Campaign observations of ionospheric plasma irregularities in the sporadic E-region using FormoSat-3/COSMIC satellites and the Chung-Li radar", K.I. Wang "Application on FormoSat-3/COSMIC GPS RO data on global and environmental studies", J. Wickert on "Remote sensing of the atmosphere with navigation satellites", C.H. Lin on "Probing the ionosphere by the global navigation satellite system and the FormoSat-3/COSMIC constellation", and J.Y. Liu on "The GPS Science Application Research Center - GPSARC". This first day was closed with an icebreaker session in a Chung-Li city hotel at which all the students and lecturers took part.

The exclusive lectures of ISAR started on Wednesday, 8 October 2008, by Jens Wickert, Germany, teaching on the basics of "Remote sensing of the atmosphere with navigation satellites" followed by M.C. Yen of NCU, Taiwan, on "Space and ground-based sounding and monitoring" in the afternoon. During the following days further expansions and extensive lectures were given by J. Wickert, and by C. Rino, USA, on "Wave propagation, scintillation, and remote sensing", T.C. Chiu, NCU Taiwan, on "Data retrieval algorithms in FormoSat-3 GPS Radio Occultation methods", K. Groves, USA, on "Ionosphere scintillation from satellite observations", V.E. Kunitsyn, Russia, on "Ionosphere radio tomography and occultation technique, J. Röttger, Germany, on "Ionosphere and atmosphere research with radar", L.C. Tsai, NCU Taiwan, on "Ionospheric electron density and total electron content: Measurement and modeling", and Y.H. Chu, NCU Taiwan, on "Ionospheric study based on ground-based radar and FormoSat-3/COSMIC data".

In addition to Questions and Answers sessions a tour with introduction to hardware of the local, refurbished NCU VHF radar was done. On Monday, 13 October, a tour to the National Space Science Project Office - NSPO, in nearby Hsin-Shu did take place which was guided by a presentation of N.L. Yen on "An introduction to the FormoSat-3/COSMIC program". On Wednesday, 15 October, the students were given a list of questions for the examination on Friday afternoon. The evaluation of the answers by the scientific directors showed that the majority of the students had gained well from the school lectures. On Saturday, 11 October, a sight-seeing tour to Taipei and environment took place, which was guided by Jason Wu.

The students were mostly from the developing countries in the South-East Asian region. Out of almost 93 applications 34 students could be selected, namely from India (7), Indonesia (8), Japan (1), Malaysia (2), Nigeria (2), Philippines (6), Vietnam (1), and Taiwan (7).The students got air ticket refund, a daily allowance, free local transportation and lunch packages, and free accommodation at the NCU Guesthouse. The necessary assistance for students and lecturers as well as the smooth performance of the school was assured by Local Organizing Committee under Prof. Lung-Chih Tsai and by the very efficient and friendly work from the local staff. The Scientific Organizing Committee was working together with the school co-directors Prof. Lung-Chih Tsai and Prof. Jürgen Röttger.

The school activities were only possible by the generous funding and supporting provisions by the National Central University (NCU), the National Science Council (NSC), the Academia Sinica, the Ministry of Education (MoE), the College of Earth Sciences of NCU, Center of Space and Remote Sensing Research (CSRSR) at NCU, the Graduate Institute of Space Science of NCU, Department of Atmospheric Science of NCU, National Space Science Office (NSPO), and the International Union of Radio Science (URSI), and the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP).

In summary, the Sustainable Development Forum of NCU in combination with the ISAR-NCU school workshop and intense lectures gave the participants and in particular the students a very important introduction and overview of radio science used for remote sounding by satellites and radar. The next school of this kind with some extension towards radio propagation effects is planned to possibly take place at the National Central University in autumn 2009. More information on ISAR-NCU can be found at http://isarncu.ncu.edu.tw.

This school is an activity of URSI Joint Working Group GF.2. The directors of ISAR-NCU-2008, J. Röttger and L.C. Tsai, thank URSI Commissions G and F for sponsor-ing and providing financial support.

Jürgen Röttger and Lung-Chih Tsai

CONFERENCE ANNOUNCEMENTS

ISTET '09

Lübeck, Germany, 22 - 24 June 2009

The 15th edition of the International Symposium on Theoretical Electrical Engineering, ISTET'09, will be held in Lübeck, Germany, from 22 to 24 June 2009. The unique feature of this symposium is to bring together all theoretical aspects of electrical engineering, particularly fields and networks, as well as related applications. High-frequency networks, electromagnetic compatibility issues, new materials, and interconnection design are a few topical examples for the need of expertise in the entire field of theoretical electrical engineering.

Topics

Several examples of main topics are listed in - but are not limited to - the following:

Electromagnetic fields

- Fundamental aspects of field theory
- Analytical and numerical approaches
- Computational electromagnetics
- Optimization in electromagnetics
- Special techniques for low and high frequency problems

Networks and system theory

- Fundamental aspects of networks and system theory
- Advances in non-linear networks
- New concepts for circuit analysis
- Combined lumped and distributed parameter systems

Signal processing and identification

- Advanced methods for signal processing
- Non-linear dynamics and signal processing
- Classical and non-classical aspects in identification
- Neural networks
- Biomedical signal processing

Applications (Examples)

- Electromagnetic compatibility
- Nondestructive testing
- Inverse problems
- Bioelectromagnetic fields and waves
- Nanomaterials for applications in electrical engineering
- Fields and circuits for mobile communications
- Control systems
- Electrical drives and power systems
- Nano and Quantum-Engineering

New approaches in educating theoretical EE

- Innovative ideas for courses on fields, circuits and systems
- Multimedia in teaching theoretical EE
- E-learning approaches and results

Contact

Ludger Klinkenbusch
Conference Chair Organising Commitee
University of Kiel, Germany
lbk@tf.uni-kiel.de

COSPAR 2010
38th Scientific Assembly of the Committee on Space Research and Associated Events

Bremen, Germany, 18 - 25 July 2010

Topics

Approximately 90 meetings covering the fields of COSPAR Scientific Commissions (SC) and Panels:

- SC A: The Earth's Surface, Meteorology and Climate
- SC B: The Earth-Moon System, Planets, and Small Bodies of the Solar System
- SC C: The Upper Atmospheres of the Earth and Planets Including Reference Atmospheres
- SC D: Space Plasmas in the Solar System, Including Planetary Magnetospheres
- SC E: Research in Astrophysics from Space
- SC F: Life Sciences as Related to Space
- SC G: Materials Sciences in Space
- SC H: Fundamental Physics in Space
- Panel on Satellite Dynamics (PSD)
- Panel on Scientific Ballooning (PSB)
- Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS)
- Panel on Radiation Belt Environment Modelling (PRBEM)
- Panel on Space Weather (PSW)
- Panel on Planetary Protection (PPP)
- Panel on Capacity Building (PCB)
- Panel on Education (PE)
- Panel on Exploration (PEX)
- Special events: Interdisciplinary lectures, space agency round table, etc.

Contact

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http://www.cospar2010.org/ or
http://www.cospar-assembly.org

Scientific Program Chair

Prof. Tilman Spohn
Institute of Planetary Research
German Aerospace Center (DLR)

Abstract Deadline

The abstract deadline is mid-February 2010. Selected papers published in Advances in Space Research, a fully refereed journal with no deadlines open to all submissions in relevant fields.

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/Calendar of supported meetings

January 2009

EMC Zurich 2009
Zurich, Switzerland, 12-16 January 2009
Contact: Dr. Pascal Leuchtmann, ETH Zurich, ETZ K94, CH-8092 Zurich, Switzerland, Fax +41 44-632 1647, Leuchtmann@ifh.ee.ethz.ch , Web: http://www.emc-zurich.ch

February 2009

International Workshop on Chorus Plasma Waves
La Jolla, CA, USA, 18-20 February 2009
Contact: Bruce Tsurutani, Jet Propulsion Laboratory MS 169-506, 4800 Oak Grove Dr., Pasadena, CA 91109, USA, Fax: +1 818 354 8895, E-mail: bruce.tsurutani@jpl.nasa.gov

May 2009

MST 12 - 12th Workshop on Technical and Scientific Aspects of MST Radar
London, Ontario, Canada, 17-23 May 2009
Contact: Wayne Hocking and Toshitaka Tsuda, Co-chairs, MST workshop series, Web: http://www.mst12.com/

12th Workshop on the Physics of Dusty Plasmas
Boulder, CO, USA, 18-20 May 2009
Contact: Dr. Zoltan Sternovsky, Laboratory for Atmospheric and Space Physics, UCB 392, Boulder, CO 80309-0392, Fax: +1 303 492 0642, E-mail: zoltan.sternovsky@colorado.edu, Web: http://wpdp.colorado.edu/index.php

URBAN 2009 - Data fusion and Remote Sensing in Urban areas
Shanghai, China, 20-22 May 2009
Contact : Shanghai Association for Science and Technology (SAST), No.47 Nanchang Road, Shanghai 200020, China (SAST), Fax: 86-21-6327 1590, E-mail: urban-urs2009@163.com, Web: http://www.urban-remote-sensing-2009.org.cn, Web: http://www.mst12.com/

June 2009

EMC 2009 - VIII International Symposium and Exhibition on Electromagnetic Compatibility and Electromagnetic Ecology
St. Petersburg, Russia, 16-19 June 2009
Contact : St.Petersburg State Electrotechnical University "LETI" , 5, Prof. Popov Street, St. Petersburg, 197376, Russia Underground Station "PETROGRADSKAYA", Fax: +7 812 234-46-81, E-mail: discone@mail.wplus.net, Web: http://www.eltech.ru/emc

ISTET-09 - International Symposium on Theoretical Electrical Engineering
Luebeck, Germany, 22-24 June 2009
cf. Announcement in the Radio Science Bulletin of December 2008, p. 72.
Contact: Ludger Klinkenbusch, E-mail: info@istet09.de, Web: www.istet09.de

July 2009

EMC'09 - 2009 International Symposium on Electromagnetic Compatibility, Kyoto
Kyoto, Japan, 20-24 July 2009
Contact: Prof. R. Koga, Dept. of Communication Network Engineering, Okayama University, Tsushima, Okayama, 700-8530, Japan, Fax +81 86-251-8136, E-mail: emc09@is.takushoku-u.ac.jp, Web: http://www.ieice.org/emc09/contacts.html

September 2009

Metamaterials 2009
London, UK, 1-4 September 2009
Contact: Dr. Richard W. Ziolkowski, E-mail: ziolkowski@ece.arizona.edu, Web: http://congress2009.metamorphose-vi.org/

ICEAA'09 - International Conference on Electromagnetics in Advanced Applications
Turin, Italy, 14-18 September 2009
Contact: ICEAA 07, Politecnico di Torino , Corso Duca degli Abruzzi 24 , 10129 Torino, Italy, Fax: +39-011-564-5199, e-mail: gspinasanta@corep.it, Web: http://www.iceaa.net/

October 2009

International Conference on Radar
Bordeaux, France, 12-16 October 2009
Contact: SEE / CONGRESS DEPARTMENT, Béatrice Valdayron - Valérie Alidor - Caroline Zago - Morgane Melou, Fax: + 33 (0)1 56 90 37 08, E-mail : radar2009@see.asso.fr , Web: http://www.radar2009.org

February 2010

META '10 - Second International Conference on Metamaterials, Photonic Crystals and Plasmonics
Cairo, Egypt, 22-25 February 2010
Contact: Dr. Said Zouhdi, Laboratoire de Génie Electrique de paris, LGEP-Supélec, Plateau de Moulon, 91192 Gif-sur-Yvette Cedex, France, Fax+33 1 69 418318, E-mail: said.zouhdi@supelec.fr, Web: http://meta10.lgep.supelec.fr

April 2010

AP-EMC 2010 - Asia-Pacific EMC Symposium
Beijing, China, 12-16 April 2010
Contact: Web: http://www.apemc2010.org

July 2010

COSPAR 2010 - 38th Scientific Assembly of the Committee on Space Research (COSPAR) and Associated Events
Bremen, Germany, 18 - 25 July 2010
cf. Announcement in the Radio Science Bulletin of December 2008, p. 73.
Contact: COSPAR Secretariat, c/o CNES, 2 place Maurice Quentin, 75039 Paris Cedex 01, France, Fax: +33 1 44 76 74 37, E-mail: cospar@cosparhq.cnes.fr, Web: http://www.cospar2010.org/ or http://www.cospar-assembly.org

August 2010

EMTS 2010 - International Symposium on Electromagnetic Theory (Commission B Open Symposium)
Berlin, Germany, 16-19 August 2010
Contact: EMTS 2010, Prof. Karl J. Langenberg, Universität Kassel, D-34109 Kassel, Germany, E-mail: info@emts2010.de , Web: http://www.emts2010.de

URSI cannot be held responsible for any errors contained in this list of meetings.

News from the URSI Community

NEWS FROM THE MEMBER COMMITTEES

EGYPT

26th National Radio Science Conference

Faculty of Engineering, Future University, Cairo, Egypt, 17-19 March 2009

The Egyptian National URSI Committee would like to announce its 26th National Radio Science Conference, which will be held in the Faculty of Engineering, Future University, Cairo, from 17-19 March 2009.

Topics of interest are the 10 commission of the URSI.

The Paper submission deadline is set on November 15th, 2008

Contact

Prof. Ibrahim A. Salem
Academy of Scientific Research and Technology
101- Kasr El-Nil, Cairo- Egypt -11561
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salem_ibrhm_32@yahoo.com
htpp://www.futureuniversity.edu.eg

FRANCE

Journées Scientifiques d'URSI-France "Propagation et Télédétection"

CNAM, 292 Rue Saint-Martin, Paris, 24-25 Mars 2009

Les Journées scientifiques se tiendront au CNAM, 292 rue Saint-Martin, Paris 3ème et débuteront le mardi 24 mars à 9h30. Elles seront suivies le mercredi 25 mars, vers 16h par l'Assemblée générale d'URSI-France.

Elles sont organisées autour de sessions animées par des spécialistes reconnus du domaine. Ces sessions seront introduites par des conférences invitées présentant soit l'état de l'art, soit de nouveaux développements intéressant l'ensemble de la communauté, suivies de communications orales. Celles-ci seront sélectionnées par le comité scientifique. La sélection tiendra compte de l'équilibre des sujets présentés dans chaque session.

Sauf exception, la langue de travail est le français; toutefois les planches accompagnant les présentations pourront être rédigées en anglais.

Les Journées scientifiques 2009 d'URSI-France, placées sous le haut patronage de l'Académie des sciences auront pour thème « Propagation et télédétection ». Ces journées se tiendront au Conservatoire national des arts et métiers (CNAM) à Paris.

L'accent sera porté sur :

- La caractérisation, la modélisation, la capacité du canal de transmission pour des liaisons terrestre, maritime et spatiale afin de présenter des modèles de propagation fiables dans différentes bandes et largeurs de fréquences (micro-onde, millimétrique, terahertz) ;
- La relation entre la complexité de l'environnement et le nombre de modes (chemins de propagation). L'influence des effets tels que les mécanismes de propagation (réflexion, transmission, diffraction, diffusion, guidage, …, etc.), la dépendance en fréquence, la position des antennes, la polarisation, la nature des matériaux, la présence et le déplacement des personnes, le mobilier, la végétation seront pris en compte.
- Les méthodes tirant profit des propriétés du canal de transmission : techniques de diversité, retournement temporel, mitigation, … ;
- La prise en compte par les différents systèmes des propriétés de la propagation ; notamment en télédétection active et passive,
- L'évolution des bases théoriques de la détection suite au développement, d'une part, d'une grande variété de radars et, d'autre part, des nouvelles technologies : antennes et traitement de signal ;

- L’observation de la Terre, des surfaces et des composantes de son atmosphère : méthodes, outils, échelles, moyens de mesure, besoins futurs et enjeux liés à l’environnement, … ;
- Les grandeurs physiques ; le perfectionnement des moyens d’observation invite à une réflexion sur les grandeurs physiques mesurées et leur étalonnage.

Comité Scientifique

Jean Isnard, Président, URSI-France
Pierre Bauer, Météo-France
Madhukar Chandra, Univ. Chemnitz
Jean Marc Conrat, Orange Labs
Monique Dechambre, Univ. Versailles Saint Quentin
Pierre Degauque, Université de Lille 1
Christophe Delaveaud, CEA Ghais El Zein, IETR
Jean-Claude Imbeaux, Orange Labs
Jean-Marc Laheurte, Univ. Marne-la-Vallée
Patrick Lassudrie-Duchesne, TELECOM-Bretagne
François Le Chevalier, Thales
Joël Lemorton, ONERA
Marie-José Lefevre-Fonollosa, CNES
Geoffroy Lerosey, LOA, ESPCI
Marc Lesturgie, ONERA/ESE
Thierry Marsault, CELAR
Didier Massonnet, CNES
Daniel Maystre, Institut Fresnel
Patrice Pajusco, Orange labs
Joseph Saillard, Univ. Nantes
Hervé Sizun, URSI-France
Piotr Sobiesky, Univ. Catholique de Louvain
Michel Sylvain, Univ. Marne-la-Vallée
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Joël Hamelin, URSI-France
Hervé Sizun, URSI-France
Michel Sylvain, Univ. Marne-la-Vallée
Michel Terré, CNAM
Joe Wiart, URSI-France

Publications

Les textes des communications seront consultables en ligne sur le site d’URSI-France : http://ursi-france.institut-telecom.fr

Après avis du Comité scientifique, certains auteurs seront invités à remettre leur contribution pour publication : soit dans un numéro thématique « Propagation et télédétection » des Comptes rendus Physique de l’Académie des sciences soit dans la Revue de l’électricité et de l’électronique (REE). Responsable des publications : Jean Isnard

Dates à retenir

- 15/01/2009 : clôture de réception des propositions de communication. Ces propositions seront soumises en ligne via Internet au format pdf via le site : http://ursi-france.institut-telecom.fr sous la forme d’un texte clair et concis d’une à deux pages, permettant une bonne évaluation scientifique. Toutes les informations concernant le format des propositions de communication seront disponibles sur le site.

- 10/02/09 : réponse du Comité scientifique aux proposants.

- 10/03/09 : date limite de dépôt en ligne des textes des communications.

- 24 et 25/03/09 : Journées scientifiques.

- 25/03/09 : liste des textes sélectionnés pour publication

Inscription et Informations complémentaires

Une participation aux frais de 180 € sera demandée à tous les participants. Elle comprend entre autres les collations et pauses café. Un tarif réduit de 80€ est accordé aux étudiants et seniors.

Pour 46 € supplémentaires le numéro thématique « Propagation et télédétection » des Comptes rendus Physique de l’Académie des sciences, reprenant les principales contributions de ces journées, vous sera adressé dès sa parution début 2010.

Vous pourrez trouver les modalités d’inscription et toutes informations utiles relatives aux Journées scientifiques 09 sur le site d’URSI-France: http://ursi-france.institut-telecom.fr

POLAND
XII National Symposium of Radio Science

Warsaw, Poland, 16 - 17 June 2009

The XII URSI National Symposium of Radio Science will be held in Warsaw, Poland at the **Warsaw University of Technology** from 16th to 17th June 2009.

The URSI'2009 Symposium is organized by the Military Communication Institute and Institute of Radioelectronics, Warsaw University of Technology, under the auspices of the Committee of Electronics and Telecommunications of the Polish Academy of Sciences.

The Symposium language is Polish, but English papers will be accepted and can be presented at the conference.

Topics

Topics cover all the URSI areas of interests, eg,:

- Electromagnetic Metrology
- Electromagnetic Fields and Waves in Non-Ionized Environment
- Waves in Plasmas
- Electromagnetics in Biology and Medicine
- Electromagnetic Noise and Compatibility
- Signals and Systems Theory
- Radio Astronomy
- Satellite, Space and Ionospheric Radio Communication
- Radio Navigation
- Identification and Location of Radio Signals
- New Methods and Techniques in Radio Science

Contact

URSI'2009 Conference Secretariat
05-130 Zegrze ul.
Warszawska 22A, Poland
tel. +48 22 6885503
fax. +48226885544
e-mail: ursi@ursi2009.pl
Conference Website: http://www.ursi2009.pl/

KKRRiT 2009

In parallel with the URSI'2009 The National Conference on Radiocommunication and Broadcasting (KKRRiT 2009) will be held, at the same venue, from 17th to 19th June 2009.

The main organiser of the KKRRiT 2009 is the Institute of Radioelectronics, Warsaw University of Technology.

Main **topics** of the KKRRiT 2009 are:

- Cellular Mobile at the Step to 4th Generation
- Mobile television
- Ultra wideband systems

but the scope of the conference includes all aspects of radiocomunications and broadcasting.

Contact details are :
KKRRiT 2009 Conference Sekretariat:
Instytut Radioelektroniki,
Politechnika Warszawska
ul. Nowowiejska 15/19,
00-665 Warszawa, Poland
tel. +48222347910
fax: +48228256555
Website: http://kkrrit.ire.pw.edu.pl

International Geophysical Calendar 2009 *

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

S	M	T	W	T	F	S	
			1	2	3	4	JULY
5	6	7 F	8	9	10	11	
12	13	14	15 *	16 *	17	18	
19	20	21	22 N	23	24	25	
26	27	28	29	30	31	1	
2	3	4	5	6 F	7	8	AUGUST
9	10	11	12	13	14	15	
16	17	18	19 *	20 N *	21	22	
23	24	25	26	27	28	29	
30	31	1	1	3	4 F	5	SEPTEMBER
6	7	8	9	10	11	12	
13	14	15	16	17	18 N	19	
20	21	22 *	23 *	24	25	26	
27	28	29	30	1	2	3	
4 F	5	6	7	8	9	10	OCTOBER
11	12	13	14	15	16	17	
18 N	19	20 *	21 *	22	23	24	
25	26	27	28	29	30	31	
1	2 F	3	4	5	6	7	NOVEMBER
8	9	10	11	12	13	14	
15	16 N	17 *	18 *	19	20	21	
22	23	24	25	26	27	28	
29	30	1	2 F	3	4	5	DECEMBER
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 F	1	2	2010
3	4	5	6	7	8	9	JANUARY
10	11	12	13	14	15 N	16	
17	18	19 *	20 *	21	22	23	
24	25	26	27	28	29	30 F	
31							
S	M	T	W	T	F	S	

N NEW MOON F FULL MOON

20 Regular World Day (RWD)

21 Priority Regular World Day (PRWD)

18 Quarterly World Day (QWD) also a PRWD and RWD

7 Regular Geophysical Day (RGD)

9 10 World Geophysical Interval (WGI)

+ Incoherent Scatter Coordinated Observation Day

26 Day of **Solar Eclipse**: **Jan 26** (annular) and **Jul 22** (total)

22 23 Airglow and Aurora Period

2 * 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 2009 the WGI are February, May, August, and November.

2009 Solar Eclipses:

a) **January 26, 2009, annular eclipse**, up to 7 m 54 s, visible in Indonesia (southern Sumatra, western tip of Java, and most of Borneo). Partial phases will be visible from southern Africa, southern India, southeast Asia, and western Australia.
b) **July 22, 2009, total solar eclipse**, the longest in the 18 year 11 1/3-day Saros series, with maximum of 6 m 39 s in mid-Pacific. The eclipse begins in the rainy season in India, crosses the eastern tip of Nepal, Bangladesh, Sikkim, Bhutan, northernmost Myanmar, China from west to east (including Wuhan, Hangzhou and Shanghai, with over 5 min of totality and close to 6 min on the central line between them), and some southern Japanese islands. The partial phases will be visible from all of China, from western Russia, most of southeast Asia, and the northern tip of Australia's Cape York.

Information provided by Jay M. Pasachoff, Chair, International Astronomical Union Working Group on Eclipses based on calculations from Fred Espenak, NASA's Goddard Space Flight Center, and information from Jay M. Pasachoff, Peterson Field Guide to the Stars and Planets; see 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 2008:

- Aug 12, 05:30 UT, Perseids: encounter with the 1479-dust trail of 109P/Swift-Tuttle, enhancement on top of strong annual shower; Aug 12, about 01h UT: possible encounter with older Filament debris of 109P/Swift-Tuttle;
- Nov 18, about 21:38 UT, Leonids: encounter with the 1-day wide Filament component of bright meteors, peak at about Nov 18 18:59 UT with rate ZHR = 20 /h;
- Dec 20, 08:10 UT: alpha-Lyncids (RA = 138º, Decl. = +44º): possible encounter with 1-revolution dust trail of unknown parent comet;
- Dec 22, about 03:42 UT, Ursids: possible outburst from 8-hour wide Filament of comet 8P/Tuttle.

b*) Regular meteor showers:* The dates (based on UT in year 2008) for regular meteor showers are:

- Jan 01-Jan 06, peak Jan 04 02:00 - 09:30 UT (Quadrantids);
- Apr 16-Apr 25, peak Apr 22 06:45h UT (Lyrids);
- Apr 19-May 28, peak May 04 15h UT, broad component centered on May 07 05h UT (Eta Aquariids);
- May 22-Jul 02, peak Jun 07 05h UT (Daytime Arietids);
- May 20-Jul 05, peak Jun 09 04h UT (Daytime Zeta Perseids);
- Jun 05-Jul 17, peak Jun 28 04h (Daytime Beta Taurids);
- Jul 08-Aug 19, peak Jul 28 11h UT (S. Delta Aquariids);
- Jul 17-Aug 24, peak Aug 12 16:10 UT (Perseids);
- Sep 26-Oct 03, peak Oct 01 07h UT (Daytime Sextantids);
- Oct 02-Nov 07, peak Oct 21 18h UT (Orionids);
- Oct 31-Nov 23, peak Nov 17 05h UT (Leonids);
- Nov 27-Dec 18, peak Dec 13 20:10 UT (Geminids);
- Dec 17-Dec 26, peak at Dec 22 15h UT 2008 (Ursids).

Meteor Shower Websites:

- Shower names and data (IAU Meteor Data Center): http://www.astro.amu.edu.pl/~jopek/MDC2007/index.php
- Shower activity near-real time reports (International Meteor Organization): http://www.imo.net
- Announcements and reports of meteor outbursts (Minor Planet Center): http://cfa-www.harvard.edu/iau/cbet/RecentCBETs.html
- Annual shower activity forecast for given location (Peter Jenniskens): http://leonid.arc.nasa.gov/estimator.html
- Shower outburst activity forecast (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 (Draft Edition): The following material was reviewed in 2008 by spokesmen of IAGA, WMO and URSI as suitable for coordinated geophysical programs in 2009.

- **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 tricity.** 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 7 January 2008 at 0000 UT, 14 January at 0600 UT, 21 January at 1200 UT, 28 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 21 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: (**Note – 2009 program being developed at this time.)**

CAWSES – Climate and Weather of the Sun-Earth System, (S. Avery – susan.avery@colorado.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);

C/NOFS: Communications/Navigation Outage Forecasting System (Odilie de LaBeaujardiere – Odilie.delaBeaujardiere@hanscom.af.mil)

Stratospheric Warmings = Dynamics and temperature of the lower thermosphere during sudden stratospheric warming – ten days of observation in February (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 Quasi-Periodic Medium-Scale = Latitude dependence of the F-Region plasma variations during the passage of medium-scale Traveling Ionospheric Disturbances (MSTIDs) – continuous vertical power profiles through E/F regions (100-800 km) with best time resolution possible (5 minutes or better) (J.D.Mathews — JDMathews@psu.edu)

International Polar Year continuation of year-long observations with Jicamarca, Poker Flat, EISCAT Svalbard ISRs (Tony van Eyken — Tony.van.Eyken@eiscat.se)

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/2009WDschedule.htm for complete 2009 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 Susan Avery (susan.avery@colorado.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) 2007-2009** – 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 2009 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.

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Note: an alphabetical index of names, with coordinates and page references, is given on pages 92-107.

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