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ELF and VLF radio waves ☆

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Abstract

This review covers developments in ELF and VLF radio-wave propagation research over the last 50 years of the Journal of Atmospheric and Solar-Terrestrial Physics. A review of such a large field, over such a long period, cannot be fully comprehensive and the authors have therefore covered important areas which have they themselves have found interesting. The survey begins with a review of work on natural and man made sources of ELF and VLF radiation. This is followed by sections on experimental and theoretical studies of unperturbed (ambient) ELF and VLF radio propagation. Schumann resonance research, which is currently undergoing a renaissance, is then reviewed. A review of research into transient perturbations of ELF and VLF propagation follows, extending from the early work on nuclear explosions up to the current work on sprites. The review concludes with a brief summary of the VLF navigation systems of the USSR and USA, (Alpha and Omega) whose development and life-span covered most of the last 50 years. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Earth-ionosphere waveguide; Schumann resonances; Sprite; Trimpi

1. Introduction

This paper is concerned with the generation and propagation of ELF (extremely low frequency: 3 Hz–3 kHz) and VLF (very low frequency: 3 kHz–30 kHz) electromagnetic waves in the Earth-ionosphere duct. The study of the propagation of such low-frequency (or long-wavelength) radio waves was a mature area of research even when the first issue of the Journal of Atmospheric and Terrestrial Physics was published in 1950. In fact, the famous Russian theoretician Ya.L. Al'pert, writing in his book (Al'pert, 1960) about radio propagation work in the 1950s said, 'Thus, after an interruption of 40 years, there has been renewed interest in long radio waves'!

A lot of this renewed interest was as a result of the experience gained in the Second World War of the value of radio research in communications and navigation (Buderi, 1999). The period of this review also covers the whole of the period of the 'cold war' with the associated development of nuclear weapons and their deployment on deeply submerged submarines. Communications with submarines immersed in the conducting sea necessitated the use of VLF waves and later ELF waves, with their comparatively large skin depths in salt water. This need for navigation and communications with submarines and the need for reliable global military communications was the indirect driving force behind most of the developments in VLF and ELF radio wave propagation theory and experiment over the last 50 years.

Within a finite review it is impossible to give a detailed review of the developments in the whole subject of ELF and VLF radio waves over the last 50 years. Thousands of papers have been written during this time, many hundreds by a single author (James R. Wait)! We have therefore chosen to pick a few topics, which we have found both interesting and significant, and describe how they have evolved over the years. We have selected a subset of the published papers

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☆ The authors would like to dedicate this review to the memory of two outstanding radio-scientists whose careers spanned the last 50 years of the Journal of Atmospheric and Solar-Terrestrial Physics and who sadly died recently, P.V. Bliokh and J.R. Wait.

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which, in our opinion, best show the development of the topic. This will therefore be a personal account of ELF and VLF radio-wave propagation over the 50 years of the existence of the Journal of Atmospheric and (Solar-)Terrestrial Physics.

2. Natural sources of ELF and VLF radio waves

ELF and VLF transient signals and noise are generated by various natural and artificial phenomena. Those of natural origin include the familiar lightning discharges from thunderstorms, volcanic eruptions, dust storms and tornadoes. At high latitudes, noise emissions generated by charged particles (polar chorus, broad-band auroral hiss), occasionally dominates all of the lightning generated noise at ELF frequencies, and noise spectra in polar regions often contain the characteristic signature of polar chorus in the 300 Hz–2 kHz range. However, on a global basis, by far the most significant source of noise at ELF and VLF is that generated by lightning discharges. In 1990 upward electrical discharges were observed above thunderclouds. Associated high-altitude luminous phenomena called sprites, elves and blue-jets have been identified in the past six years. These phenomena too, have ELF and VLF radio effects, which are discussed in this paper.

2.1. Thunderstorms, lightning and sprites

The lightning discharge is an electrical breakdown current which may flow from cloud to ground (CG discharge) or within thunderclouds (intra-cloud or IC discharge). Ground to cloud (GC) discharges are rare, usually occurring from mountain tops and tall buildings. The discharge currents generate transient radio pulses termed ‘atmospherics’ or ‘sferics’. Due to the dominance of sferics generated by lightning in the ELF and VLF bands, they are the only source considered here.

Examples of references concerned with the lightning source characteristics and statistics are Malan (1963), Galejs (1972), Ogawa (1982), and (especially) the standard monograph by Uman (1969). Malan (1963) details the methods and photographic equipment employed by early lightning investigators. The familiar cloud to ground (CG) discharge has been studied most extensively since much of the discharge path is external to the cloud and can be photographed and studied using optical instruments. The total lightning discharge, lasting about 0.2 s, is termed a ‘flash’ and is comprised of several (1–30, but typically 4) ‘strokes’ separated by about 50 ms and lasting for a few to tens of milliseconds. Each stroke is preceded by a low luminosity ‘leader’ process. This produces a negatively charged channel between cloud and ground which is then neutralized by a high current (tens of kiloamps) ‘return stroke’ progressing up the leader channel with a velocity $\sim 10^8$ m/s. The large majority of CG lightning flashes, designated negative-CG (or ‘$-$CG’), lower negative charge to Earth. The proportion is $\sim$90% in mid-latitudes but this decreases in the tropics.

Both CG and IC discharges generate sferics. However, an important prediction of the radio propagation theory is that *ELF-band* sferics are not produced effectively by horizontal components of lightning, i.e. horizontal IC discharges. Nevertheless, the *vertical component* of IC discharges (and the intra-cloud portions of CG discharges) will generate these sferics. According to Teer and Few (1974), the structure of IC discharges and the intracloud portions of CG lightning may be modelled as being contained in an ellipsoid whose long axis is parallel to the Earth’s surface. The vertical component of an IC discharge is about 1/3 of the total discharge path in this model. However, IC strokes may have discharge paths much longer than CG strokes and thus produce comparable ELF sferic amplitudes.

It has been estimated that about 2000 thunderstorms are in progress around the world at any time. The global flash rate is of order 100 per second (Orville and Spencer, 1979). Measured noise statistics from the Stanford Radiometer project (Chrissan and Fraser-Smith, 1996) contain essentially no contributions from other natural sources. Lightning activity is highest in the summer months in the tropics and while thunderstorms tend to occur over mountainous regions there is significant activity over the oceans.

There are three main centres of global lightning activity in South Africa, Central and South America and South Eastern Asia. Examples of global lightning activity maps are those presented by Uman (1969) (these show DMSP satellite data) and by the CCIR (1990). Williams (1992) illustrates the variation of lightning activity with latitude (as observed from space) showing that two of every three lightning flashes occur in tropical latitudes. Lightning activity moves from the northern to the southern hemisphere as the northern hemisphere winter sets in. Characteristics of thunderstorm activity are, therefore, expected to be dependent on geographic location and local meteorological and seasonal conditions. Precise data on temporal and spatial variations were once scarce, but observations from the Ionospheric Sounding Satellite (ISS-b) have been published (Kotaki et al., 1981) and on-line data from the Optical Transient Detector satellite (launched in 1995) are now available (NASA, 2000).

Sprites (or ‘red sprites’) are extended red luminous columns which can be observed at night using low-light television (LLTV) cameras. They appear as clusters of short-lived ($\sim$50 ms) pinkish-red luminous columns, stretching from $\sim$ 30 to $\sim$ 90 km altitude. They are generally less than 1 km wide and occur above active thunderstorms — especially so-called ‘mesoscale convective systems’. They are primarily associated with large-amplitude positive cloud-to-ground discharges (see Section 4.1.2), although by no means *all* such discharges generate sprites. Red sprite observations have been made from the ground, from aircraft, and the US Space Shuttle. Recent reviews are those of Rodger (1999) and Jones (1999).

2.2. Models of the lightning discharge and ELF/VLF wave generation

Statistically, lightning parameters are usually well represented by a 'log-normal' probability distribution. Ogawa (1982) gives typical and extreme values for various lightning parameters as originally compiled by Uman (1969) and modified with statistical data from Cianos and Pierce (1972) and others. The latitude dependence of source characteristics is also of importance. This has been reviewed by Warber and Field (1991) and is a feature of their global atmospheric radio-noise computations.

If spatial distributions and temporal variations of the currents in a stroke are known, the radiated fields from the channel can be calculated in the time or frequency (Fourier) domains. The first useful model of the return stroke current waveform was produced by Bruce and Golde (1941). This models the lightning current at the ground by a sum of two exponentials, i.e. $I(t) = \sum_1^K I_k \mathrm{e}^{-\omega_k t}$, with $K = 2$.

The Bruce-Golde model has been used by many workers, mainly on account of its analytical simplicity. It appears to account adequately for the characteristics of sferics propagated over ranges exceeding a 100 km or so. More complex models are required if the observer is nearer the source (Uman, 1969). Hepburn (1957a) added a third exponential term ($K = 3$) to account for the strokes responsible for slow tail sferics (about 1/3 of the total strokes). These have considerable energy in the ELF range and are enhanced by continuing currents in the channel (see Section 4.1.1). In a comprehensive review of data relating to lightning radiation, Williams (1959) derived a median return stroke model which was extensively used by Galejs (1967a) and Jones (1970a) in discussions of models of the lightning stroke currents.

Jones (1970a) combined the considerations of Williams (1959), Pierce (1963), Hepburn (1957a) and others to derive a model of the first and subsequent cloud-ground discharges that includes the effects of the leader and return strokes. An increase in the channel length with increasing order of stroke is a feature of this model. A Bruce-Golde-type representation of the current flowing at the ground during the return stroke is used with $K = 4$. The significance of each of the terms is illustrated using 'Bode diagrams'. This model has a median peak current for the primary stoke (determined essentially by the $k = 1$ and 2 terms) of 24 kA and time-to-peak of 5.5 μs. An important parameter in the generation of sferics is the total charge moment change ΔM_Q of the thundercloud — Earth-image dipole produced by the discharge current. For a median discharge this is of order 100 C km. However, analyses of ELF 'event' sferics and some near-field observations (see Jones and Kemp, 1971) have shown that ΔM_Q can be as large as 3000 C km in the large-amplitude 'tail' of the lightning statistics. This large value of ΔM_Q is considered to be produced mainly by a long continuing current in a single-stroke flash with an amplitude of ~10 kA and an average time constant of about 30 ms (Burke and Jones, 1996).

2.3. Sprites and ELF wave generation

The connection between sprites (see Section 2.1), lightning and ELF waves has been reviewed by Jones (1999) and is outlined here in Section 4.1.2. Sprites appear to be generated *almost* entirely by +CG (positive CG) lightning return stroke discharges with large peak currents (currents $\geqslant \sim 35$ kA), and large ΔM_Q values (thousands of coulomb-kilometres). Very recently, two sprites thought to be generated by negative CG lightning have been observed by the Stanford group (Barrington-Leigh et al., 1999).

The first evidence for slow-tail sferics generation by in-sprite currents was presented by Cummer et al. (1998a). Even more recently, Stanley et al. (2000), present convincing data which shows the generation of a slow tail sferic (with no VLF radiation) more than 13 ms after a +CG return stroke and which is probably produced by an energetic sprite event. Interestingly, this signal was generated in daytime when sprites cannot be observed optically because of their low light intensity. This research area is developing rapidly. It is true, however, that nearly all sferics are generated directly by lightning strokes and only a minority of these produce the upper-atmosphere optical phenomena discovered over the past decade.

3. Man-made sources of ELF and VLF radio waves

To radiate electromagnetic waves efficiently one needs an antenna whose dimensions are of the order of the wavelength of the radiation. VLF waves, with frequencies from 3 to 30 kHz, have wavelengths from 100 to 10 km and this suggests that VLF antennas must be extremely large to be efficient. With ELF waves (3–3000 Hz) the corresponding wavelengths range from 100,000 to 100 km and an ELF antenna needs to be enormous to have an efficiency of any practical significance. This problem of scale has been a challenge to radio engineers and we will briefly describe some of the innovative attempts to circumvent it. We will then describe in more detail the work on the generation of ELF and VLF waves by powerful HF heaters. This technique is still under active development and a HF transmitter for the world's most powerful facility is still under construction in Alaska.

3.1. VLF antennas

At VLF the ground-based vertical electric monopole antenna can operate at reasonable efficiency, especially at frequencies above 10 kHz. This type of antenna has been the mainstay of VLF communications system for most of the twentieth century. The antennas are very large, typically many hundreds of metres long and are usually strung between high towers. VLF antennas often make use of natural geographic features for support, they have been strung across fjords in Norway and in extinct volcanoes in Hawaii. Using a balloon lofted electric monopole antenna, Koons and Dazey (1983) managed to radiate significant amounts of energy at frequencies as low as 6 kHz. However, the prize for the most ambitious balloon lofted antenna must go to Field et al. (1989). Using a very long vertical antenna ($\sim$ 3.8 km) they obtained efficiencies of $\sim$ 90% at 25.3 kHz and even suggested using balloons at ELF. They radiated $\sim$ 40 mW of energy at 104 Hz. This represented an efficiency of some 1.6 W radiated per MW of input power to the transmitter. An excellent book on the engineering of VLF antennas was written by Watt (1967). It has recently been suggested, that in situations where directional VLF antennas are strategically acceptable, a long horizontal travelling wave antenna, of the Beverage type, can have significant environmental advantages (King, 1997).

The US Navy developed airborne VLF transmitters for use in the event of the outbreak of war, when normal land-based VLF antenna arrays would make an easy target. The aircraft were known by the name TACAMO, an acronym for Take Charge And Move Out. Not only were these aircraft able to generate, within the aircraft itself, the significant amounts of VLF power needed for reliable communications but they were also able to deploy 35,000 feet of antenna within less than 45 min (Swanson, 1974).

More exotic types of VLF antenna have been suggested which make use of natural geographical structures. Morgan (1960) suggested that Deception Island, located near the end of the Antarctic peninsula, might serve as a natural, resonant, slot antenna. Independently, Gould (1961) injected ELF/VLF current into a conductor connected across the isthmus of a peninsula in Scotland and observed resonances in the impedance of the conductor near 10 kHz. He ascribed these to currents flowing around the peninsula. He also measured small VLF fields up to 2 wavelengths from the conductor. However, theoretical work by Galejs (1962) and Staras (1963) showed that, whilst the slot/peninsula antenna idea was generally correct, the conductivity contrast between sea water and the rock comprising the island was too small for an effective system.

It has also been suggested that an efficient ELF antenna might be constructed by passing a loop of wire through a tunnel under a mountain and closing the loop over the peak of the mountain (Burton et al., 1983). This idea was taken up by Barr et al. (1993) who placed a wire through the Homer tunnel in Fiordland, New Zealand, and completed a horizontal magnetic dipole antenna by passing the wire over the top of the mountain through which the tunnel was excavated. The tunnel was 1.2 km long and at its apex the wire loop was 600 m above the centre of the tunnel. The system radiated 75 mW for every kilowatt of input power at 10 kHz. Signals were detected over a range of frequencies from 500 Hz to 60 kHz at a site 200 km from the transmitter.

3.2. *ELF Antennas*

Vertical electric antennas are not efficient at ELF (Field et al., 1989). In comparison with VLF antennas they are a shorter fraction of a wavelength in length, and thus their radiation resistance is much lower. Also, they have higher input impedance and thus sources of greater voltage are needed to produce a significant antenna current. For ELF systems the antenna of choice is the horizontal, insulated grounded-end dipole or line current antenna. The most ambitious antenna of this type was that designed for Project Sanguine. The design for this enormous facility, which was planned to cover an area in the US some 100 km square, is covered in detail in the book by Burrows (1978). Although very efficient for an ELF antenna the efficiency would only have been some 100 W/MW. The early tests for the Sanguine ELF system are described by Willim (1974). Sadly the system never got off, or perhaps we should say in, the ground. Currently, the US has two ELF antenna sites, one in Wisconsin and one in Michigan. These use single grounded horizontal wires with a length of about 150 km and they are synchronously driven to facilitate global communications. The system is said to radiate 10 W at 76 Hz (Jones, 1995).

Fraser-Smith and Bannister (1998) recently detected signals at 82 Hz, at a number of widely spaced recording sites. They attributed these signals to a Russian ELF communications system operating on the Kola Peninsula. The system consists of 2 parallel antennas about 60 km long. These are connected to generators which provide currents of between 200 and 300 A over the frequency range 20–250 Hz (Velikhov et al., 1996). The Russian system appears to be about 10 dB more powerful than the US system and clear signals have been detected even near the transmitter's antipode (Fraser-Smith and Bannister, 1998).

Proposals have also been made to deploy a long wire antenna from the Space Shuttle both to generate electric power, from its motion in the Earth's magnetic field, and also to radiate ELF signals (Grossi, 1982). An attempt was made to do this in 1996. Sadly the wire fractured when 19.7 km long, before it had been fully deployed from the Space Shuttle (GRL, 1998). Whilst the experiment terminated prematurely the system generated much more power than expected prior to its demise. This technique could be an area of significant development in the future.

3.3. *'Wireless' antennas*

3.3.1. *Amplitude modulated HF heating*

A number of different schemes, employing the interaction of HF radio waves in the ionosphere, have been proposed for the generation of ELF and VLF signals. To date the greatest success has been achieved by modulating natural currents flowing in the ionosphere using powerful, amplitude modulated, HF transmitters, the heated patch of ionosphere acting as a dipole at the modulation frequency, immersed in the ionospheric plasma. The first reported detection of

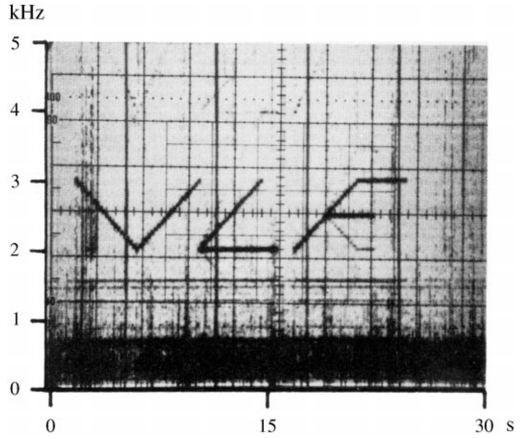

Fig. 1. Spectrograph of VLF waves generated by modulation of an ionospheric current using the Tromsø heater (from Stubbe et al., 1982a,b).

signals radiated by this technique was presented by Getmantsev et al. (1974). The signals were very weak and, in providing a theoretical explanation for the observations, Kotik and Trakhtengerts (1975) suggested repeating the experiment at higher latitudes in a region of stronger natural current flow. Kapustin et al. (1977) made measurements at higher latitudes under the auroral electrojet but although their data clearly showed how the ELF signals were correlated with magnetic activity, and hence natural current flow in the ionosphere, only relative amplitude data were presented. A summary of early Russian heating work is presented by Belyaev et al. (1987).

Between 1977 and 1980 a very powerful HF heating facility was constructed, beneath the auroral electrojet, at Tromsø, in northern Norway. Stubbe et al. (1981) presented the first near-field measurements of the VLF signals radiated from the ionosphere above the facility. They recorded signals $\sim$100 μV/m at Lavangsdalen, 18 km from the transmitter site. However, Stubbe et al. (1982b) were the first to give a truly literal interpretation to the phrase 'VLF radiation from the ionosphere' (see Fig. 1). The first reliable far-field signals from the facility were recorded by Barr et al. (1985a) at Kiruna and Lycksele, in Sweden, 205 and 554 km from the transmitter, respectively. They computed the ELF power radiated by the system to be of the order of a few watts between 1 and 2 kHz, for an input power of 1 MW, a figure in good agreement with the theoretical computations of Barr and Stubbe (1984a). To date the HIPAS heating facility, in Alaska, holds the record for the range at which ELF signals have been detected from the heated ionosphere (excluding satellite measurements). In 1990 and 1991 Bannister et al. (1993) received 154 Hz signals in Connecticut, 5.2 Mm from the transmitter facility in Alaska. A review of ELF and VLF wave generation experiments at the major heating facilities, prior to 1998, was presented by Barr (1998).

ELF signals radiated by the unintentional modulation of the auroral electrojet have also been reported. Turunen et al. (1980) heard 1 kHz timing pips on their ELF receivers operating in Northern Scandinavia which they considered were produced by the non-linear demodulation of amplitude modulated transmitters operating in the USSR. Further data were presented by Cannon (1982) who observed that the occurrence of pip demodulation was associated with periods of increased magnetic disturbance. Cannon et al. (1982) provided a series of different scenarios for oblique heating by broadcast transmitters in Northern Europe to explain the observations of Cannon (1982).

The efficiency of ELF wave generation by amplitude modulated HF heating is predicted to decrease markedly with decreasing modulation frequency (Barr and Stubbe, 1984a). As a result sophisticated enhancement schemes, such as the 'beam painting' technique of Papadopoulos et al. (1989, 1990), will need to be successfully implemented if ELF wave generation by modulated HF heating is ever to be a viable proposition. Taranenko et al. (1992) have suggested that significant gains in ELF generation efficiency may be obtained by operating HF heaters at frequencies > 5 MHz. They suggest that, whilst below 5 MHz the modulated Hall current is the dominant ELF current source (Barr and Stubbe, 1984b), above 5 MHz Pedersen current modulation will become dominant, and that ELF generation efficiencies should then increase by a factor of from 4 to 30 times.

The world's most modern HF heating facility, that of the HF active Auroral Research Program (HAARP) has begun initial operations in Alaska. This facility, in its final configuration, is specifically designed to enable trials of the 'beam painting' efficiency enhancement techniques proposed by Papadopoulos et al. (1989,1990). It will also be able to operate at the higher frequencies required to test the theories of Taranenko et al. (1992). We await the results from this facility with interest.

3.3.2. Amplitude modulated VLF heating

It has been suggested that VLF waves may cause a measurable heating of the ionosphere (Galejs, 1972) and this is discussed more fully in Section 7. More recently, it has been proposed that VLF waves, amplitude modulated at ELF, may be a more effective means of generating ELF radiation than amplitude modulated HF waves (Taranenko et al., 1992). Taranenko et al. (1992) claim ELF radiation efficiencies $\sim$100 mW/MW comparable with or larger than those obtained by HF heating.

3.3.3. ELF/VLF wave generation via the cubic non-linearity mechanism

Finally, it should be noted that it is also possible to generate ELF/VLF radiation using the 'cubic non-linearity' mechanism described by Ginzburg (1964). Using this technique Kotik and Ermakova (1991) generated ELF and VLF waves through the interaction of 2 HF waves in the ionosphere.

The HF wave of higher frequency had a frequency equal to twice that of the low-frequency wave, plus an offset in the ELF/VLF range. Barr (1997) has found that this interaction also works with the 2 VLF waves producing a third VLF (or possibly ELF) wave. He suggests 2 VLF transmitters of appropriate frequency, working near the magnetic equator, could possibly provide an effective source of ELF radiation. This technique has the advantage that it does not rely on natural current flow in the ionosphere.

3.4. Nuclear explosions

In the 1950s and 1960s, the USA, USSR and the UK conducted a large number of nuclear tests from below the sea surface to high in the atmosphere. It was found that nuclear explosions produced strong impulsive VLF signals that showed a spectral peak in the vicinity of 10–15 kHz (Glasstone, 1962; Helliwell, 1965). In a similar way to lightning impulses, it was found that some of the nuclear VLF impulses also led to the generation of whistlers (Allcock et al., 1963; Helliwell, 1965). High-altitude detonations appear to have been particularly effective in producing VLF signatures (Crook et al., 1963; Croom, 1965). However, the fact that Jean and Wait (1965) used signatures from 7 explosions in the Redwing series, which were mainly surface detonations, as sources for studying the propagation of VLF waves in the Earth-ionosphere waveguide, shows that low-altitude explosions were also significant sources of VLF radiation. They observed the nuclear impulses at Stanford and Boulder, typically 8000 and 9400 km from their source. That they could do this, in the presence of significant interference from lightning, suggests the nuclear sources were quite substantial. Electronics techniques have improved significantly since the early 1960s, and accurate timing, at widely spaced stations, has now become generally available thanks to the Global Positioning System Satellites (GPS). It should now be a simple and cheap task to locate any atmospheric nuclear explosions globally using their VLF signatures in a similar way to that used for locating lightning (Lee, 1986).

4. Experiments in ELF and VLF wave propagation

4.1. Research using sferics

4.1.1. Classical VLF and slow tail sferics

The earliest experiments in ELF and VLF propagation were made using the bursts of transient electromagnetic radiation from lightning discharges, commonly termed sferics. Sferics are short pulses, typically of 1–10 ms duration (see Fig. 2), whose vertical electric field can reach values as large as 1 V/m even at ranges of over 1000 km (Taylor, 1960). They have a significant spectral content over the whole ELF/VLF range and have been used in studies of radio wave propagation in the Earth-ionosphere waveguide for more than 50 years. The early observations were basically attempts at classification of different sferic types (Hepburn, 1957b, 1958) but for more quantitative propagation studies it was necessary to determine the amplitude spectrum of the sferic pulses. Two different techniques were initially used for studying these short pulses. Bowe (1951), Taylor (1960), Al'pert et al. (1967), and Challinor (1967a) produced photographic records of the sferic transients that they then digitized and Fourier transformed to produce amplitude spectra. Bowe (1951), Chapman and Matthews (1953), Chapman and Macario (1956), Taylor (1967) and Barr (1970) used narrow band electronic filters tuned to different frequencies for which the amplitude spectrum was required.

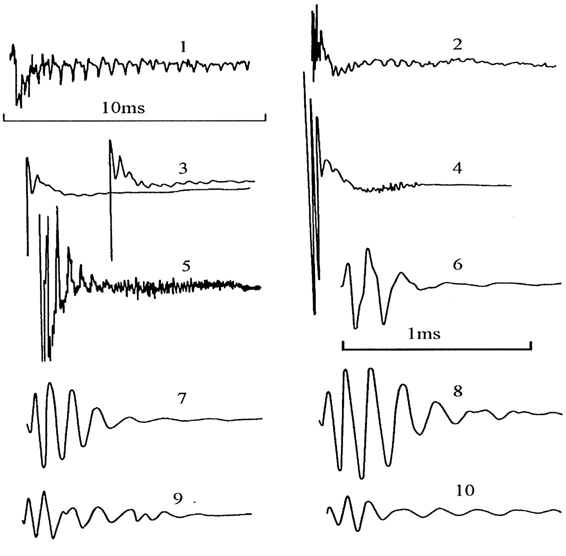

Fig. 2. Typical atmospheric waveforms. Traces 1–5 were recorded with a 10 ms timebase. Traces 6–10 were recorded with a timebase slightly longer than 1 ms (from Hepburn, 1957b).

By observing the amplitude spectrum of sferics of gradually increasing range Chapman and Macario (1956) made the first estimate of the attenuation constant of the Earth-ionosphere waveguide at audio frequencies (100 Hz–12.5 kHz). By measuring amplitude spectra of sferics simultaneously at widely spaced stations Taylor (1960) deduced attenuation rates in the VLF band and Jean et al. (1960) obtained phase velocity data over the same frequency range. Croom (1964) presented waveguide attenuation data from 1 to 15 kHz, relative to the attenuation at 7 kHz, using simultaneous data from 5 stations. Challinor (1967a) observed sferic spectra simultaneously in London, England and Jersey in the Channel Islands. From these spectra he evaluated the complex propagation constant of the Earth-ionosphere waveguide under daytime and nighttime ionospheres. He then derived two inhomogeneous isotropic model ionospheres which exhibited complex propagation constants similar to those observed experimentally

(Challinor, 1967b). A good summary of this early sferics work, especially the work at King's College, London, is presented in Chapman et al. (1966).

Two types of sferic, the 'slow tail' and 'tweek', have received special attention in radio-wave propagation studies. The slow tail sferic (Hepburn, 1957a) has been used mainly in the studies of ELF propagation whereas the tweek sferic (Hepburn, 1957b) has been used to study nocturnal VLF and upper ELF-band propagation. Tweeks were originally referred to as echo-type waveforms (Horner and Clarke, 1955) and simple ray theory analyses were used to model their propagation between the Earth and the ionosphere. The range of the sferic from the VLF receiver and the equivalent height of the ionosphere, assumed homogeneous, were derived from these simple models. Williams (1966), from measurements on the polarization of tweek waveforms, was able to deduce that a sharp gradient in electron density of the nocturnal ionosphere near 90 km was needed to produce tweek sferics. A particularly interesting use of tweek sferics was the paper by Reeve and Rycroft (1972) who used them to monitor the change in the effective height of the ionosphere during a solar eclipse. Yamashita (1978) used waveguide mode theory to model the propagation of tweek sferics below a homogeneous anisotropic ionosphere. More recent theoretical work on tweeks has been presented by Ryabov (1992) and Yedemsky et al. (1992). Sukhorukov (1996) has produced analytical VLF models which can produce tweek sferic spectra and, like Williams (1966), has also stressed the requirement of sharp electron density gradients near 90 km. The most recent observations and analysis of tweek sferics has been presented by Cummer et al. (1998b). They measured the fine structure of the amplitude spectra of tweek sferics and matched it to the fine structure in theoretical spectra. The theoretical spectra were derived from an analysis of nocturnal propagation under anisotropic ionospheres whose electron density varied exponentially with height. From this modeling they deduced a 2 km increase in the effective height of the ionosphere from North to South across the United States at the time of the experimental measurements.

A detailed statistical study of the occurrence of slow tail sferics was presented by Hepburn (1957a). Wait (1960) presented a theoretical model of the generation and propagation of slow tail sferics in terms of the waveguide mode theory and re-analyzed the data of Hepburn (1957a). He found a linear relationship between the square root of the temporal separation, between the VLF oscillatory head of the sferic and the maximum of the ELF slow tail, and the distance to the lightning discharge. Assuming propagation under homogeneous isotropic ionsopheres he was able to deduce the effective conductivity of the ionospheres needed to describe both the daytime and nighttime slow tail data accurately. Taylor and Sao (1970) used the low-frequency energy in slow tail sferics to measure the ELF propagation constant of the Earth-ionosphere waveguide. They obtained useful data from 20 to 300 Hz. Jones (1970b) reviewed the data then available on slow tail sferics and presented computed slow tail for the various source models discussed in Section 2.2.

Hughes (1971) measured the amplitude ratio of ELF spectral components from multiple stroke lightning flashes simultaneously at two remote sites. He found differences in the ratios that he ascribed to either horizontal components in the discharge or electron heating in the ionosphere by the VLF component of sferics. This is probably one of the earlier works to consider ionospheric heating by VLF waves from lightning (see also Inan et al., 1993). With the improvements in electronic and computer technology since the early 1950s we can expect a greater use of sferics for D-region studies in the future.

4.1.2. Sferics in the lower-ELF band (transient excitation of the Schumann resonances)

The closing years of the 1990s have witnessed an explosion in papers concerned with sferics as observed in the lower ELF band (3–60 Hz). A recent review devoted to this topic and the 'sprite-connection' is that of Jones (1999). Huang et al. (1999) details many new research results and give a good critique of the field, providing nearly 100 references. There is insufficient space here to do justice to the very many different facets of this research area or to the authors involved. We have thus chosen to concentrate on a research aspect that appears particularly promising at the time of writing.

In the lower ELF band, the attenuation suffered by globally propagating electromagnetic waves is extraordinarily small. It amounts to only 0.3 dB/1000 km at 10 Hz, increasing with frequency to about 1 dB/1000 km at 60 Hz (see Fig. 3). This low attenuation rate allows the Schumann resonances (SR) (see Section 5) to be prominent in sferic noise spectra and enables the radiation from intense individual lightning flashes to be detected at global ranges. These unusually powerful lightning discharges produce a large signature in the lower ELF band that appears as a transient pulse ('Q-burst' or transient 'event') in a waveform record. This pulse stands out above the Schumann resonance 'background' sferic noise produced by world-wide lightning activity (Ogawa et al., 1966a). Distinguishable transient events arrive at a rate of about one or two per minute. They have a duration of order 0.5 s and exceed the background (of r.m.s. amplitude ~1 mV/m or 3 pT in the band 5–50 Hz) by a factor of three or more. Much more information can be obtained from the analysis of such events than from sferic noise spectra because they are radiated by a single source at certain location on the Earth's surface.

The first detailed analysis of these events was reported by Jones and Kemp (1970). These authors showed that the geographical location of the lightning source could be inferred from the SR-mode-structure of the electric and/or magnetic field spectra of the transient signal recorded at a *single* observing station. The signals have since been used to deduce the characteristics of the unusual source lightning

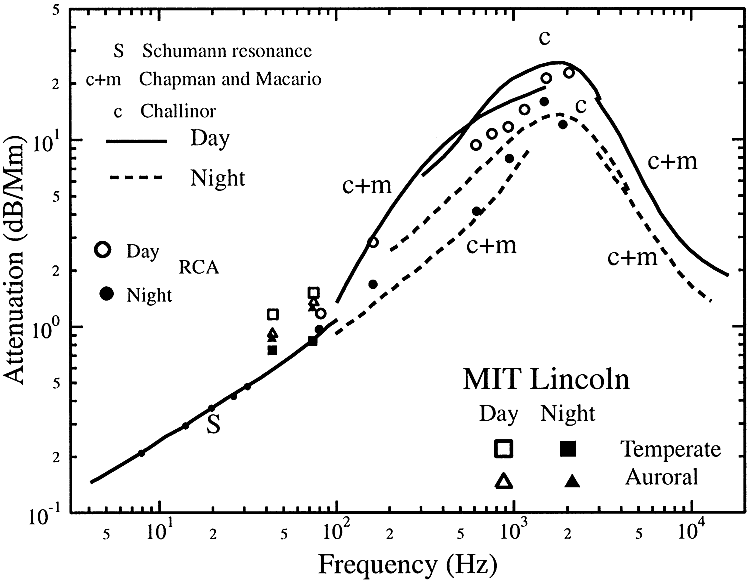

Fig. 3. The attenuation constant of the Earth-ionosphere waveguide in the frequency range 1 Hz–10 kHz (after Bernstein et al., 1974).

strokes and for propagation studies as well as for locating their sources. For these investigations the analysis technique introduced by Kemp and Jones (1971) has many advantages. This involves computing the frequency-domain wave impedance $Z(\mathrm{i}\omega)$ (the ratio of the Fourier transforms of the experimental E and H field components) of the event waveform. It follows from the theoretical equations for the field components that this wave impedance is independent of the complexities of the lightning source characteristics and thus contains only information on the propagation characteristics (the attenuation constant α and the phase velocity ratio c/v) and the source–observer range d. There are advantages in using both the amplitude and phase of the complex quantity Z (Ishaq and Jones, 1977). A development of the method has been detailed by Nickolaenko and Kudintseva (1994). Burke and Jones (1992) used the wave impedance method combined with a computer optimization algorithm to deduce the variation of ELF attenuation rate with latitude, showing that the attenuation was markedly higher in polar regions than in temperate latitudes.

There has been much interest in mapping (or ‘fixing’) the sources of ELF events using the wave impedance method. The first global map, published by Kemp (1971), showed 50 fixes, and was obtained using analogue instruments. Later data are those of Burke and Jones (1995) (who analyzed 261 signals using a computer optimization algorithm) and Huang et al. (1999) (who present thousands of fixes *per month*, though these are obtained by a simplified, less-precise, method). All these use data from a single recording site. In contrast, Füllekrug and Constable (2000) have used a global network of three stations (in Germany, California and Australia) to triangulate sources. Boccippio et al. (1998) used OTD-satellite data (Section 2.1), to estimate the accuracy of their ELF source location technique, thus providing ‘ground-truth’ validation of the method.

From the earliest days of these studies, all observers have agreed that the majority ($\sim$70%) of these large-amplitude ELF signals have a positive E-field polarity (Kemp, 1971; Burke and Jones, 1996; Huang et al., 1999). A recent very large data-set illustrating this phenomenon is that of Füllekrug and Reising (1998). The polarity of the field indicates that the source discharge is positive, i.e. it corresponds to a lowering of positive charge to the ground. The source *could* thus be a +CG discharge (Section 2.3) having a large charge-moment change.

The connection between ELF events, positive CG lightning and sprites (Section 2.3) has received considerable attention in the literature following the ground-breaking investigation of Boccippio et al. (1995). This showed that some 80% of sprites were coincident with +CG lightning discharges *and* ELF transient events. More recently, Huang et al. (1999) report a very detailed study and both these papers and that by Füllekrug and Constable (2000) include a good discussion of source characteristics. Data provided by the US national lightning detection network (NLDN) (Wacker and Orville, 1999) has been crucial in much of the reported work.

The current interest in these transient events is that they have the potential of enabling global lightning, meteorological factors and sprite generation to be investigated by ELF radio observations made at very few sites or even at a single station. Experiments increasingly involve many individuals (to observe simultaneously sprite occurrence, GC discharges and ELF signatures at widely separated geographical places). We conclude with a quotation from the 10-author paper of Williams et al. (1999) — "The rough proportionality between the intensity of the background SR … and the number of large positive transients … is welcome news to students of SR. This result suggests that the tail of the global lightning distribution (which is mappable from a single SR station) should serve as a quantitative measure of the total lightning distribution … ."

4.2. Research using transmitter generated ELF/VLF signals

4.2.1. Fixed location recording (ELF)

The first long-range ELF propagation studies over a wide frequency band were made by the RCA Laboratories in 1966–1967 (Ginzburg, 1974). Signals from 78 Hz to above 1 kHz were radiated from a long horizontal wire antenna located in North Carolina. Receivers were located in New York, Labrador and Iceland. Later the M.I.T. Lincoln laboratory made ELF attenuation measurements using the Wisconsin Test Facility (WTF) transmitter (see Fig. 3). Measurements were made of the average attenuation rates and phase velocities of ELF waves in the ranges 40–50 and 70–80 Hz (Bernstein et al., 1974; White and Willim, 1974). Measurements of signals radiated by the WTF were subject to intense scrutiny over the next decade and it was found that the nocturnal propagation in particular was subject to marked variability (see Bannister, 1982 and references therein). Theoretical explanations for the variability have been sought in terms of the effects of sporadic ionization in the E-region (Barr, 1977; Pappert, 1980) and in energetic electron precipitation (Davies, 1974). Field et al. (1986) have used two-dimensional ray tracing to model the effects of large ionospheric anomalies on ELF propagation. Most recently, Fraser-Smith and Bannister (1998) have made the first observations near the antipode of an ELF transmitter and obtained excellent agreement between experimental measurements and theoretical computations.

4.2.2. Fixed location recording (VLF)

In the early years covered by this review the most popular means of studying the D-region of the ionosphere was by observing its effect on VLF transmitter signals propagating beneath it. Belrose (1956, 1957) obtained useful data for sunspot minimum conditions whereas Bracewell et al. (1951) obtained data representative of sunspot maximum. These were short-path ground-based observations, performed at fixed locations, from which the reflection and conversion coefficients of the ionosphere could be derived for comparison with theory (see Section 5.1). The technique was later used with some success to study the propagation of VLF radio signals over short paths during a solar eclipse (Crary and Schneible, 1965; Sales, 1967).

Significant discoveries have also been made by observing and then modeling the propagation of VLF signals over long paths. Kaufmann and Schaal (1968) and Hoy (1969) observed phase anomalies on very long VLF propagation paths (13.3 and 17.1 Mm, respectively) during solar eclipses. However, the first attempt to model accurately the effect of a solar eclipse on long-path VLF propagation was made by Noonkester and Sailors (1971). They produced a combined VLF propagation and D-region aeronomy model which they used with some success in modeling the effects of the eclipse of 11 September 1969 on 12.2 kHz signals from Omega Hawaii received in Aztec, Arizona. Later work on the effects of solar eclipses by Lynn (1981) suggests that the phase anomalies observed experimentally for a given propagation path are not linearly related to the solar obscuration function for that path.

Brady and Crombie (1963) observed changes in the height of the ionosphere of ~0.1 km from observing phase changes at Boulder, Colorado of signals from the transmitter NBA (18 kHz) in the Canal Zone. They claimed that these changes were evidence of a semi-diurnal lunar tidal variation in the ionosphere. Using the long North–South propagation path from Seattle (NLK 18.6 kHz) to Byrd Station, Antarctica, Bernhardt et al. (1981) have also observed the influence of lunar tides on the ionosphere. They also claimed to have observed a hebdomadal variation in VLF amplitude. They found that VLF amplitudes were 0.46 dB greater during Sunday daylight hours relative to the Monday–Saturday average. They ascribed this effect to man-made changes in the D-region.

Crombie (1964a) made observations of the periodic amplitude and phase changes over long VLF paths. He explained his observations in terms of multi-mode propagation in the Earth-ionosphere waveguide but with the added contribution of modal conversion at sunrise and sunset produced by the changes in waveguide height. By making simultaneous observations from both fixed and moving platforms Walker (1965) was able to confirm some of the significant predictions of Crombie's theory. Pappert and Morfitt (1975) later developed sophisticated computer models for studying the effects of modal conversion at sunrise and sunset. Recently, Clilverd et al. (1999a) have made some interesting long-term studies of propagation over a long North–South path from Cutler, Maine (NAA on 24 kHz) to Faraday, Antarctica. This path has the interesting property in that for a short period of the year, near the equinox, the leading edge of the terminator crosses the whole propagation path within 20 min. The authors found that the timings of minima in received signal strength were consistent with modal conversion taking place as the sunrise terminator crossed the propagation path, at specific, consistent locations. They also found the timings of the minima to be remarkably consistent from year to year. It would be interesting to study this excellent data set in the manner described by Bernhardt et al. (1981).

Crary and Crombie (1972) observed signals from the transmitter GBR (16 kHz) near Rugby, England, at Byrd Station in Antarctica. From these observations they were

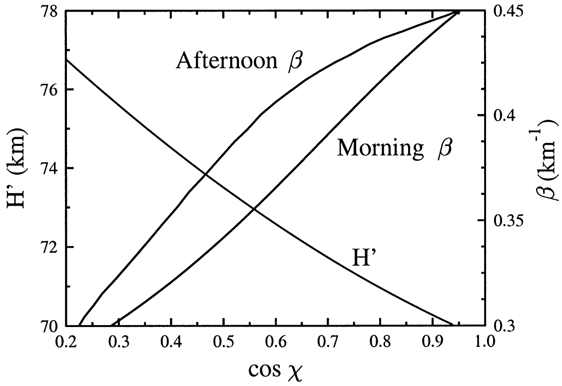

Fig. 4. The dependence of β and H' on solar zenith angle (after Thomson, 1993).

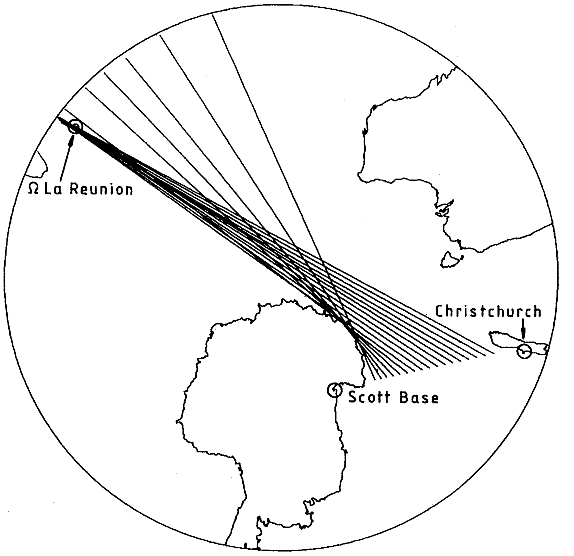

Fig. 5. Typical propagation paths of signals from Omega, La Reunion, received on an aircraft flying between Christchurch, New Zealand and Scott Base, Antarctica showing the effects of diffraction around the Antarctic icecap (after Barr, 1987).

able to deduce the magnitude of the extra attenuation suffered by VLF signals when propagating over glacial ice. Westerlund and Reder (1973) extended work in this area, both theoretically and experimentally, with observations on the Greenland ice-sheet. They also derived values of conductivity and dielectric constant of glacial ice that best fitted their experimental data.

Thomson (1985) observed signals from NWC, NPM and NLK in Dunedin, New Zealand using an innovative cross-correlation technique on the MSK signals. With this system he was able to detect the presence of VLF signals reflected from the Andes and the Rocky Mountains. These results were later modelled by Wait (1992).

Thomson (1993) determined the solar zenith angle dependence of the exponential ionospheric model parameters β and H' introduced by Wait and Spies (1965) for use with the VLF propagation prediction model of the Naval Oceans Systems Center (see Fig. 4). He derived the parameter values and their zenith angle dependency from observations on two, nearly North–South VLF propagation paths, one short (620 km) and the other long (6.7 Mm). The midday value of β came mainly from the attenuation on a very long path across the Pacific.

4.2.3. *Mobile VLF recordings*

Weeks (1950) recorded VLF transmitter signals as a function of range obtaining an interference pattern for comparison with theoretical estimates. This technique, originally developed in the UK by Hollingworth (1926), has proved to be very powerful. Bickel et al. (1957, 1970) presented data from a series of flights to and from Hawaii, on different azimuths, recording signals from the transmitter NPM. The most comprehensive set of VLF flight data, covering frequencies from 9 to 56 kHz, is probably that presented by Morfitt (1977), obtained for use in deriving D-region electron density profiles (see Section 5.2).

Burgess and Jones (1975) presented airborne data on the effects of the Greenland icecap on signals from Omega Norway. They observed very rapid signal attenuation (20–40 dB/Mm) when flying over the icecap. Barr (1987a) observed Omega signal strengths on flights from New Zealand to Antarctica. He found that not only were the signals from some Omega transmitters attenuated by passage over the ice cap, as reported by Burgess and Jones (1975), but that some signals were also diffracted around the ice cap leading to significant errors in Omega position fixes (see Fig. 5).

Barr and Helm (1982) made observations of the signals from the transmitter NWC (22.3 kHz) in Australia when flying over the Southern Alps in New Zealand. They observed periodic changes in amplitude and phase of received signals that they interpreted as standing waves in the Earth-ionosphere waveguide produced by signals reflected from the Southern Alps. In a more comprehensive experiment Barr and Armstrong (1996) observed standing waves in signals from Omega and communications transmitters when flying over the Rocky Mountains (see Fig. 6). It would be interesting to repeat the last two experiments under different wind regimes. It is just possible that some of reflected signals resulted from Bragg scattering from periodic variations in the ionospheric electron density generated by mountain waves (Schoeberl, 1985).

Rogerson (1967) and Bickel (1967) made airborne VLF measurements in Southern Africa, flying through the antipode of the transmitter NPM (19.8 kHz) in Hawaii. Clear effects due to antipodal focussing were recorded and the attenuation rate for 19.8 kHz waves was determined. With the new spatial Fourier transform techniques developed by Barr

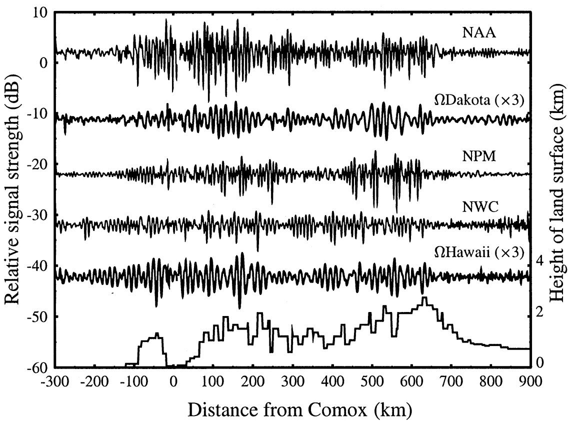

Fig. 6. Standing waves in VLF transmissions propagating over the Rocky Mountains West of Comox, Vancouver Island (from Barr and Armstrong, 1996).

(1987a) flights past the antipodes of VLF transmitters could provide data for truly global propagation studies.

5. Theory of ELF and VLF wave propagation

5.1. Short path data and ray theory

The early years of JATP saw very rapid advances in the theoretical study of the propagation of ELF and VLF radio waves. Initially, most theoretical work centered on the interpretation of the signals received from VLF transmitters after reflection from the D-region of the ionosphere at short ranges. Typically, these measurements were analyzed to produce the reflection, $_{||}R_{||}$, and conversion coefficients, $_{||}R_{\perp}$, of the ionosphere (Budden, 1966), over a range of frequencies. Model ionospheres were then sought which exhibited reflection and conversion coefficients similar to those obtained experimentally. The first ionosphere models were very basic being sharply bounded, and homogeneous, but the anisotropy produced by the Earth's magnetic field was included (Budden, 1951). Then followed a classic series of four papers entitled 'The numerical solution of the differential equations governing the reflexion of radio waves from the ionosphere', (Budden, 1955a, b; Barron and Budden 1959; Barron, 1961). These papers developed a series of alternative formulations to enable the reflection coefficient matrix of an ionosphere to be determined for arbitrary variations of electron density and collisional frequency with height. All formulations accounted for the anisotropy of the ionosphere induced by the Earth's magnetic field (see also Budden, 1966). The technique was modified by Pitteway (1965) to provide solutions in terms of the *penetrating* and *non-penetrating modes* in the ionosphere. This revised technique was then used by Deeks (1966) to derive realistic D-region electron density profiles from experimental VLF data. Profiles representative of the ionosphere at sunspot minimum were derived from data presented by Belrose (1956, 1957), and those appropriate to sunspot maximum were derived from the data of Bracewell et al. (1951). Although a great advance in remote sensing of the D-region, the technique had a weakness in that absolute reflection heights were not well established. To overcome this problem Bain and May (1967) elected to model VLF ground wave interference patterns (Weeks, 1950) using the reflection coefficients calculated with the technique described by Pitteway (1965) in a ray theory analysis. Bain and May (1967) produced a D-region profile similar in shape to that of Deeks (1966) but 6 km lower in altitude. Russian scientists (Baybulatov and Krasnushkin, 1966) independently analyzed the same British data. However, although the D-region profiles of the two groups showed the same overall trend, the minima and maxima present on the British profiles were absent on the Russian data (Bain, 1969). This observation was explained by Bailey and Jones (1974) who made quantitative estimates of the resolution of the inversion scheme used for deriving the Deeks (1966) sunspot minimum D-region profile from VLF data. They showed that the experimental data could not confirm the existence of a 'valley' in the electron density near 70 km, even though its presence was consistent with the data. This lack of uniqueness of D-region ionosphere profiles derived from VLF data is a feature of all remote-sensing methods based on inversion techniques.

Shellman (1970) and Mambo et al. (1983) have also considered the problem of deriving D-region electron density profiles from VLF reflection coefficients. Morfitt and Shellman (1977) have gone so far as to make available a FORTRAN computer program designed specifically to solve the problem. Inversion theories have also been developed to allow D-region electron density profiles to be derived form long-path ELF and VLF propagation data (Shellman, 1973). With the enormous advances in computer technology since 1973 these techniques of remote D-region sounding using ELF and VLF waves could possibly be revisited with advantage.

5.2. Long-path data and mode theory

One of the advantages of ELF and VLF radio waves, which was a significant reason for the research into them, was their ability to propagate globally without excessive attenuation. However, the ray theory is not a very convergent technique for studying propagation over paths more than 1000 km and a more convenient form of representing the VLF/ELF fields between the Earth and the ionosphere was required. This came with the concept of treating the surface of the Earth and the ionosphere as the lower and upper plates of a parallel plate waveguide, the field at any point in the guide being derived in terms of waveguide modes. Wait (1957) published a historical account of waveguide mode theory followed by a comprehensive derivation of the waveguide mode theory of VLF propagation.

According to Wait (1967) the true revival of waveguide mode theory in radio propagation came when K.G. Budden at the Cavendish Laboratory in Cambridge published a significant series of papers in the early 1950s (see Budden, 1952, 1953). Convenient references for the early work on ELF/VLF waveguide mode theory are the books by Budden (1961) and Wait (1962). Early waveguide computations assumed the Earth to be flat and the ionosphere to be homogeneous and isotropic (Budden, 1952; Chapman and Macario, 1956; Wait, 1957). More realistic approximations to the ionospheric conductivity profile were made possible by the introduction by Wait (1958) of the ionosphere stratification technique developed from a more basic two-layer model of the ionosphere. Even with a two-layer model it was possible to obtain reasonable agreement between experimental and theoretical values of attenuation constant over a wide range of frequencies (Chapman and Jones, 1964). By a simple extension of the two-layer model the propagation under any ionosphere with arbitrary variations of electron density and collisional frequency with height could be determined. Wait and Spies (1965) suggested the use of ionospheres with exponential variations of collisional frequency and plasma frequency with height for VLF propagation and such models are still accepted as the standard today (Thomson, 1993).

In solving the mode equation for propagation under an anisotropic ionsphere, when the Earth's magnetic field was taken into account, it was necessary to determine all the terms for the reflection coefficient matrix of the ionosphere for complex angles of incidence. This technique was already well developed by Budden and others (see Section 5.1) and was first used in waveguide studies by Martin (1961). The model used by Martin (1961) was somewhat unrealistic, however, in that although the electron density was assumed to vary exponentially with height, and the collisional frequency was assumed constant. Pappert et al. (1967) made the first VLF computations of propagation in what could be called a realistic Earth-ionosphere waveguide with exponential ionosphere profiles as defined by Wait and Spies (1965). The computer program of Pappert et al. (1967) also allowed for the curvature of the Earth using the modified refractive index technique devised by Booker and Walkinshaw (1946). Barr (1968) derived the propagation constant of the Earth-ionosphere waveguide from 100 Hz to 10 kHz for E–W, W–E and N–S propagation under the anisotropic ionosphere profile derived by Deeks (1966). Martin (1961), Pappert et al. (1967) and Barr (1968) all used numerical integration techniques to derive the reflection coefficients of the ionosphere but some workers preferred to use matrix multiplication techniques of Galejs (1965, 1967b,c). The textbook by Galejs (1972) provides an update on waveguide mode theory for both ELF and VLF propagation, including the effects of stratified ground conductivity.

The last significant development in VLF mode theory came with the moves to include the effects of modal conversion resulting from rapid spatial changes in the upper or lower boundary of the waveguide. Wait (1969) and Smith (1974, 1977) studied the effects of modal conversion at a land sea boundary whereas Pappert and Snyder (1972) and Pappert and Morfitt (1975) studied the effects of modal conversion produced by changes in the ionosphere over sunrise. Barr (1987b) studied the effects of modal conversion on Omega signals propagating across a sea/Antarctic-ice boundary.

As a result of all these developments it was eventually possible to solve the modal equation for a waveguide comprised of an inhomogeneous, anisotropic ionosphere and a stratified ground of finite conductivity, and then provide modal summations along a path over which the ionosphere and ground parameters changed with propagation distance. A computer program specifically designed to solve this problem, the Long Wave Propagation Capability (LWPC), was developed for the Naval Oceans Systems Center (NOSC) (Ferguson and Snyder, 1987). This program has been used by many workers, especially in the area of Trimpi research where modeling has been further developed to include the effects of ionospheric anomalies located to one side of the direct great circle propagation path (see Section 7.2.1).

6. The Schumann resonances

The Schumann resonances (SR) were discovered by W.O. Schumann just two years after the publication of the first issue of this journal (Schumann, 1952). The SR are simply the electromagnetic resonances of the global Earth-ionosphere (quasi) spherical-shell cavity. These resonances are excited by global lightning activity and are evident when sferic radio noise spectra are measured in the lower ELF band between 5 and 60 Hz at a site that is not prone to interference sources. Such interference is produced by power line transients, electric railways, Earth currents from grounding systems, mechanical vibrations of the antennas or surrounding vegetation and drifting electrically charged clouds. For perfectly reflecting boundaries, Schumann showed that the resonance frequencies are given by an equation of the form $f_n = 7.49(n(n+1))^{1/2}$. This formula predicts a fundamental mode frequency ($n = 1$) of $f_1 = 10.6$ Hz with overtones at 18.4, 26.0, 33.5 and 41.1 Hz. Developments of the basic theory may be found in the specialized text of Bliokh et al. (1980) together with the standard texts of Wait (1962) and Galejs (1972). A recent comprehensive review is that of Sentman (1995).

Much of the SR research work in the 1950s and 1960s was undertaken out of academic interest. However, from 1959 the US Navy was considering exciting the Schumann modes for communicating with submarines. Covert ELF and SR research was contracted under Naval ‘PANGLOS’ contracts. Work on the so-called ‘Sanguine’ (later ‘Seafarer’) ELF submarine communication system (see Section 3.2) began in 1981 and the system became operational in 1986. For more technical details see the IEEE special journal issue edited by Wait (1974). A non-technical overview has been given by Jones (1985).

In 1962 a specialists’ meeting was held in Schumann’s institute in Munich under the auspices of NATO. Schumann and his colleague König were in attendance and some of the earliest SR experimental results and analyses using sferic noise spectra were presented in five papers, authored or co-authored by M. Balser, R. Gendrin, D.Ll. Jones, C. Polk and M.J. Rycroft (see Blackband, 1964). In the 1950s, König published a series of papers seeking to verify the existence of Schumann’s resonances (e.g. Schumann and König, 1954) but the data obtained were controversial. It is now widely accepted that the first definite experimental confirmation of Schumann’s prediction was the MIT Lincoln Laboratory ELF noise spectral analysis of Balser and Wagner (1960, 1963), made under the PANGLOS contract. These spectra have maxima near 7.8, 14.2, 19.6, 25.9 and 32 Hz corresponding to the modes $n = 1$–5 in Schumann’s formula. The measured frequencies are lower than predicted by the formula because of ionospheric losses and are thus diagnostic of these losses. Further examples of experimental observations and data analyses during this era are the work of Madden and Thompson (1965), Rycroft (1965), Etcheto et al. (1966) and Ogawa et al. (1966b).

Non-uniformity of the Earth-ionosphere cavity produced by variations of the ionospheric characteristics over the globe are expected to produce a ‘splitting’ of the nth Schumann mode into $2n + 1$ degenerate components. This is analogous to the Zeeman effect seen in optical spectra. Experimental confirmation of the SR effect was first published by the Norwegians Egeland and Larsen (1968). The frequencies and Q-factors (i.e. bandwidths) of the SR modes seen in the noise spectra have been investigated intensively in terms of the waveguide mode theory. This work enabled both the attenuation constant α and the phase velocity ratio c/v of the propagating fields to be measured in the lower part of the ELF band (Chapman et al., 1966). The effects of various realistic ionospheric conductivity models were studied by Jones (1967), Galejs (1972) and Booker and Lefeuvre (1977) among many others. A seminal analysis of the resonances using a development of the much used Greifinger and Greifinger (1978,1979) simplified ELF propagation model has been given by Sentman (1990).

Measured spectra have been used diagnostically to compute both ionospheric profiles (Tran and Polk, 1979; Bannister, 1985) and the global distribution of lightning strokes (see, e.g., Galejs, 1972; Polk and Toomey, 1972; Nickolaenko and Rabinowicz, 1995; Nickolaenko et al., 1996). The amplitude of the Schumann modes is determined by the temporal and spatial distribution of global lightning which is most intense over the tropical land masses (South America, Africa and Indonesia). Also, the amplitude is larger in the daytime hemisphere (Sentman and Fraser, 1991). Magunia (1996) analyzes the relation between lightning and ELF noise levels on a global basis. The use of Russian single-station Poynting vector spectra to study the space–time dynamics of world-wide lightning activity has recently been reported by Belyaev et al. (1999).

The effects produced on Schumann resonances by ionospheric disturbances induced by variations in solar activity or nuclear explosions have been reported by several workers over many years. Examples are Gendrin and Polk (see Blackband, 1964), Cannon and Rycroft (1982) and, very recently, Schlegel and Füllekrug (1999). The last paper contains a well-researched list of references relevant to this topic. In particular, it is shown that solar proton events cause frequency, Q-factor and amplitude increases of the SR modes. These papers illustrate the advantage of using readily-acquired SR data to monitor changes in the ionosphere (see also Sections 3.4 and 7.1.3). The effects of various ionospheric perturbations on the resonances have been investigated theoretically by several workers, e.g., Galejs (1972) or Sentman (1983).

In the 1950s and 1960s over 100 papers concerned with SR were published. In the 1980s, world-wide SR research activity reached a nadir. However, a renaissance occurred in the 1990s which was stimulated by Earle Williams’s (1992) discovery that the Schumann resonance phenomenon is a sensitive measure of temperature fluctuations in the tropical atmosphere (and thus generally of global climate change). Using C. Polk’s six-year data set (Rhode Island, USA) Williams (1992) demonstrated a positive correlation between the monthly means of the tropical surface-air-temperature anomaly and the magnetic field amplitude for the fundamental Schumann resonance mode. A 2 K change in temperature was shown to produce a 20-fold change in lightning activity. Because the paper by M.J. Rycroft, S. Israelsson and C. Price in this issue includes a discussion of the fascinating subject of global climate-change monitoring, we do not pursue it further here.

Williams’s (1992) discovery provoked renewed interest in obtaining long-term SR data. A number of new field stations have been activated or re-activated over the past few years. In particular, a series of measurements of SR has been made in Hungary by G. Sátori and her colleagues since 1993. These have enabled daily, seasonal, annual and inter-annual variations of SR mode amplitudes and frequencies to be made (e.g., Sátori and Zieger, 1996). The records exhibit consistent annual and semi-annual variations and have been used to obtain several parameters relating to global thunderstorm activity (Nickolaenko et al., 1998).

It is clear from the list of references to this paper that ‘JATP’ and ‘JASTP’ have been primary journals for the publication of SR results. After half a century, research into the application of the Schumann resonance phenomenon is very much alive!

7. Transient perturbations of ELF/VLF propagation

7.1. Large-scale disturbances

7.1.1. Solar flares and PCA's

It was the comparative stability of the amplitude and phase of VLF radio waves that led to the development of VLF transmitters for global navigation and communication. The very existence of navigation systems, such as Omega (Gupta and Morris, 1986), testify to the long-term stability of VLF propagation and hence also to the long-term stability of the D-region of the ionosphere, where the VLF waves are reflected (see also the recent study by Clilverd et al., 1999a). However, VLF wave propagation is directly affected by large scale, transient disturbances such as solar flares and polar cap absorption events. These have been extensively studied via their effects on VLF propagation (Bailey, 1964; Burgess and Jones, 1967; Crombie, 1965; Mitra, 1974; Reder and Westerlund, 1970; Westerlund et al., 1969).

7.1.2. Celestial X- and γ-ray sources and meteors

Edwards et al. (1969) were the first to suggest that celestial X-ray sources might be monitored by observing annual phase variations on long VLF paths. They presented 3 years of observations on the 20 kHz signals from WWVL in Boulder, Colorado, received in Wellington, New Zealand, and claimed to have detected periodic variations due to the X-ray source Sco XR-1. Ananthakrishnan and Ramanathan (1969) made similar claims from long-path LF observations. However, the view that galactic X-ray sources affected VLF propagation was not universally accepted (Burgess and Jones, 1969; Poppoff and Whitten, 1969). A detailed study of the long-term effects of a number of stellar X-ray sources was presented by Svennesson et al. (1972). They echoed the comments of Edwards et al. (1969) when they concluded that 'Continuous VLF phase tracking at frequencies above 20 kHz can provide some valuable astrophysical information complementing space probe data.'

Fishman and Inan (1988) were the first to report a transient ionospheric disturbance from a γ-ray burst, GB830801. This was one of the strongest bursts ever recorded up to that time. The observation path was from GBR (16 kHz) in England to Palmer Station in Antarctica. The most recent, and most spectacular, transient perturbation of VLF propagation created by a γ-ray flare, is presented by Inan et al. (1999). The flare originated from a neutron star 23,000 light years away, known as a Soft Gamma Repeater (SGR). Transient amplitude changes of more than 20 dB and phase changes of $\sim 65^\circ$ were observed on the path from NPM in Hawaii to Palmer Station in Antarctica. A 5.16 s periodicity in the flare output, as measured on the *Ulysses* spacecraft, was also detected in the VLF signals. VLF waves have thus been used to detect a transient event that occurred 23,000 years before the first issue of JATP!

Meteor shower ionization has also been suggested as a source of VLF phase perturbations. Chilton (1961) observed phase anomalies associated with the Lyrid, δ-Aquarid and Perseid meteor showers on the 16 kHz transmission path from Rugby, England, to Boulder, Colorado. He found a plateau in the normal daily phase variation of the 16 kHz signal coincident with the times of the meteor showers. Perhaps with all the experience gained in sprite associated Trimpi work, VLF workers could now look to determine short-term correlations between meteors and VLF phase and amplitude perturbations.

7.1.3. Nuclear explosions

Before the signing of the Limited Test Ban Treaty in 1963 the US, USSR and UK conducted more than 450 nuclear tests in the atmosphere. The signing of the test ban in 1963 led to scientific research being focussed on ways of detecting illicit atmospheric tests of nuclear weapons. Within 2 years the IEEE published a special issue of its proceedings on the detection of atmospheric nuclear explosions (IEEE, 1965). The detection of nuclear explosions by their perturbing effect on the propagation of ELF and VLF radio waves was one of the techniques detailed in the special issue (Field and Engel, 1965). Most of the early detonations took place at low altitude and only affected VLF propagation on paths in the immediate vicinity of the explosion (Field and Engel, 1965). However Crombie (1964b) and Wait (1964a,b) showed theoretically that radio propagation paths need not pass directly through a patch of ionosphere, perturbed by a nuclear weapon, for VLF propagation to be affected by it.

In later testing, rockets were used to deploy the nuclear warheads and detonation altitudes ranged from a few 10s to many 100s of km. These higher altitude explosions, some in the South Atlantic (the Argus series) and some above Johnston Island in the Pacific (Hardtack I and Dominic I series) affected ELF and VLF propagation over a wide area (Peterson, 1959; Crook et al., 1963; Zmuda et al., 1963a,b). These high-altitude explosions produced VLF anomalies not only in regions that were in the line of sight to the burst but also in the shadow zones where VLF propagation paths were shielded by the Earth from the direct X and γ radiation and particle flux. The sudden remote VLF anomalies, which occurred within a few seconds of the detonation, were explained by Crain and Tamarkin (1961). They proposed the ionization agents producing the VLF anomalies were β-rays, arising from the radioactive decay of neutrons produced in the explosion (Zmuda et al., 1964). They suggested that neutrons, because they have a half-life of 13 min, could travel to appropriate regions of the ionosphere remote from the detonation before decaying. Foderaro (1964) invoked an alternative transport mechanism to the decay mechanism of Crain and Tamarkin (1961). Foderaro (1964) suggested that prompt shadow zone effects may be produced by neutrons which have been transported into the shadow zone by multiple scatterings around the Earth. Remote VLF anomalies, delayed by some minutes after the initial burst, were explained in terms of enhanced ionization produced by the longitudinal drift of geomagnetically trapped β-particles that originated in the radioactive decay of fission fragments and/or neutrons (Sechrist, 1964). Similar effects were also observed after Soviet high-altitude nuclear tests (Haave et al., 1965). High-altitude explosions were even claimed to have abruptly lowered the frequency of the first Schumann resonance by 0.5 Hz, the condition lasting for 3–4 h (Balser and Wagner, 1963).

The unreal atmosphere in scientific research at the time can be glimpsed from this complete concluding section from a paper written in 1959. 'The high-altitude nuclear detonations showed that it is possible to generate auroras of limited extent and hydromagnetic waves; a new tool is available for making controlled auroral and upper-atmosphere studies.'

7.2. *Small-scale disturbances*

7.2.1. *Indirect VLF perturbations produced by lightning*

Helliwell et al. (1973) were the first to notice an association between whistlers and long-distance VLF propagation. They found that VLF signals from Navy transmitters on the East Coast of the US, received in Antarctica, underwent sudden increases or decreases in amplitude associated with the arrival of mid-latitude whistlers. They suggested, correctly, that the anomalies resulted from increased D-region ionization produced by whistler induced particle precipitation. These increases in ionization are now commonly termed lightning induced enhancements (LIEs). The sudden VLF perturbations became known as 'Trimpis' after the field scientist Michael L. Trimpi who made the first observations in Antarctica. The perturbations were found to average about 3 dB with rise times of about 2 s and durations of about 30 s. The Trimpi events were only observed at nighttime and this was confirmed in a later study (Leyser et al., 1984). Phase advances and retardations on long VLF paths, again associated with whistlers, were first reported by Lohrey and Kaiser (1979). They observed VLF signals from NWC in Australia at Dunedin in New Zealand. Lohrey and Kaiser explained their results and those of Helliwell et al. (1973) in terms of two-mode propagation in the Earth-ionosphere waveguide. Inan et al. (1985) observed Trimpi phase perturbations at the frequencies of the Omega VLF navigation system. They suggested that ionospheric perturbations produced by whistler precipitation could affect the accuracy of navigational fixes obtained from the Omega and Loran C navigation systems.

VLF propagation perturbations on adjacent paths have been used to estimate the size and positions of patches of lightning induced enhancements (LIEs). Networks of propagation paths have been established by a number of research groups. Working with US Navy VLF transmitters, Inan et al. (1990) established receivers in California, Saskatchewan and Quebec. They concluded that occurrence statistics of simultaneous events on crossing paths were consistent with the spatial extent of the disturbed ionospheric regions being less than a few hundred kilometers. They also concluded, on statistical grounds, that scattering from disturbances located at distances greater than 100 off the great circle path was not significant. Using a network of paths further South in the US, Yip et al. (1991) concluded that the occurrence of Trimpi events over the geographical region defined by $L < 3$ may be more dominantly controlled by magnetospheric conditions than by the lightning source distribution.

Dowden and Adams (1988, 1989) observed amplitude and phase perturbations on the signals from the tansmitter NWC, on the West coast of Australia, when received at Dunedin, New Zealand. They found that all four Trimpi types (±phase perturbation, ±amplitude perturbation) were about equally frequent on the NWC signals received in Dunedin. They used two-dimensional modeling, based on Wait (1964a,c), and explained positive amplitude Trimpis and negative phase Trimpis by diffraction from LIEs not centered on the great circle propagation path. They showed that all Trimpi types are possible with a simple diffraction model, a result derived earlier by Crombie (1964b) during his work on ionospheric depressions caused by nuclear explosions. This diffraction explanation had the advantage of not requiring an invocation of multi-mode propagation (Lohrey and Kaiser, 1979) which Dowden and Adams (1988) considered was not a significant factor on the NWC-Dunedin path. They concluded that most of the Trimpis which they observed could not be explained by the LIE patches straddling the great circle path. In fact to model one frequently occurring type of Trimpi (− −), the LIE needed to be displaced laterally from the propagation path by at least 150 . They also concluded the LIE patches must have small diameters to allow scattering through large angles. However, in such cases, they found that it was necessary to assume that the LIEs were elongated, along the propagation path, to also explain strong Trimpis.

By making observations on two different VLF frequencies, at two spaced receiving stations, Dowden and Adams (1990) were able to locate LIE patches. They concluded that LIEs occurred and produced observable echoes over a whole range of longitudes from transmitter to receiver, with some LIEs occurring relatively close to the path ends. The invariant latitude of the LIE patches (ranging from 30 to 55°) was lower than expected from a uniform distribution of lightning induced electron precipitation (see Fig. 7). The VLF receiving network in New Zealand was later increased to an array of five receivers spaced over 600 . Using this new array Dowden and Adams (1993) presented results on the location of LIEs produced by many Trimpi events, 70 of which were observed on all five elements of the array during a single night in July (late winter). It was found that most LIEs that night occurred over the Tasman Sea near the great circle path from NWC to Wellington, New Zealand. The LIEs were generally some 500–2000 km from Wellington and were estimated to have North–South dimensions of 100–250 . A much greater dimension in the East–West direction was suggested to account for the very

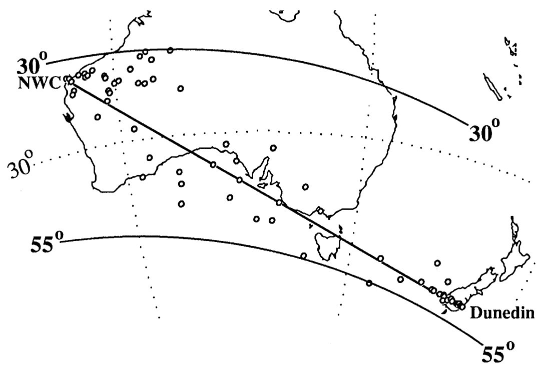

Fig. 7. Position of Lightning Induced Electron precipitation patches (open circles) deduced form observations on VLF signals from NWC in Dunedin, New Zealand (from Dowden and Adams, 1990).

large magnitude of the observed Trimpis. This tendency of LIE patches, to elongation in the East–West direction, was also observed by Smith et al. (1993).

In 1989 a VLF array for observing wave-induced particle precipitation and Trimpis was set up in Antarctica (Smith and Cotton, 1990). Two receiving stations, at Faraday and Halley in Antarctica, were used to receive signals from the transmitters in the Omega navigation network. Preliminary results indicated that Trimpi events were recorded at both receiving sites, but more often at Faraday. Most events were also of the (−+) type predicted by the single mode great circle model (Inan and Carpenter, 1987).

The observations of Inan et al. (1990) in the US, indicating that scattering from disturbances located at distances greater than 100 off the great circle path was not significant, contrasts strongly with the observations of Dowden and Adams (1988) in Australia and New Zealand. Inan et al. (1990) claim that LIEs straddle the great circle path (GCP) between transmitter and receiver whereas Dowden and Adams (1988) claim that the LIEs are adjacent to the GCP. Dowden et al. (1992), however, seem to have a possible explanation for this apparent discrepancy. They suggest that, if LIEs are very large, compared to the geometric mean of the GCP length and the VLF wavelength, or if the LIE falls off smoothly in a direction transverse to the GCP, then one will make observations similar to those of Inan et al. (1990). This is effectively a geometrical optics model. However, for LIEs smaller than this, diffraction effects are important, and then it is possible to obtain results similar to those seen by Dowden and Adams (1988) near New Zealand. A detailed review of the early work on Trimpis and sprites is given by Strangeways (1996).

Recently, Johnson et al. (1999a) found that Trimpi events, observed at multiple distributed sites, exhibited increasing onset delays with increasing geomagnetic latitude, providing the first direct evidence of precipitation of radiation belt electrons by non-ducted, obliquely propagating whistler waves triggered by lightning. This was confirmation for Friedel and Hughes (1990), who observed Trimpi amplitude perturbations in Sanae, Antarctica from European and North American VLF transmitters. Friedel and Hughes (1990) found that the Local Time pattern of occurrence of Trimpi events did not correspond to the patterns of occurrence of whistlers at Sanae. They also found that the causative whistler was rarely seen at Sanae. For these and other reasons Friedel and Hughes (1990) concluded that non-ducted whistlers may play a role in the production of Trimpi events. Lauben et al. (1999) presented the first comprehensive model of the transient precipitation of bursts of energetic electrons by oblique whistlers launched by individual lightning flashes. They were led to conclude that several previously reported lightning induced electron precipitation events, attributed to ducted whistlers, may have in fact been produced by oblique whistlers. This discovery could lead to a new interpretation of many of the Trimpi experiments described in the papers earlier in this section.

7.2.2. *Direct VLF perturbations produced by lightning*

A decade after the recognition and explanation of the “classic” Trimpi, a new type of perturbation was identified in higher time resolution data. The new perturbation had the same apparent form and decay time as the classic Trimpi, but with a very small delay (<50 ms) between the sferic and associated perturbation, implying a direct effect of the lightning on the ionosphere (Armstrong, 1983). This class of Trimpi is termed an “early Trimpi” (Inan et al., 1988).

There is, however, significant disagreement as to the primary cause of early Trimpi perturbations based on differing experimental observations. In one interpretation, based on the work of Dowden and co-workers at the University of Otago, a significant proportion of early Trimpi perturbations are caused by fine-structure plasma produced by the high-altitude discharges termed “red sprites” (see Section 2.1). The other interpretation, put forward by Inan and co-workers at Stanford University, has the rapid discharge and slow re-charging of thunderclouds modifying the lower-ionosphere through quasi-electrostatic (QE) thundercloud fields. We present the primary experimental observations (and subsequent theoretical analyses) for the two interpretations separately.

Red sprites have been reported to cause early Trimpi VLF perturbations which have been termed “VLF sprites” (Inan et al., 1995a; Dowden et al., 1996a). Red sprites are observed as clusters of short-lived ($\sim$50 ms) pinkish-red luminous columns, stretching from $\sim$3 to $\sim$90 km altitude, generally less than 1 wide and occurring above active thunderstorms (see the review by Rodger, 1999). They are primarily associated with large-amplitude (peak return stroke currents $\geqslant \sim$35 kA), positive cloud-to-ground discharges (Boccippio et al., 1995), although not for all large positive cloud-to-ground discharges. Red sprite observations have been made from the ground, from aircraft, and the US Space Shuttle (see Rodger, 1999). There is a strong body of observations that suggests that essentially all red sprites are associated with VLF sprites irrespective of their displacement from the Great Circle Path (GCP) (Dowden et al., 1996a,b,c; Dowden et al., 1998; Hardman et al., 1998). For example, Dowden et al. (1996a) first reported that red sprites caused strong scattering, even at 180° (i.e., back towards the VLF transmitter). These observations imply that the scattering source is structured enough to cause significant backscatter, suggesting that the luminous columns seen in red sprites are present in the electrical structure and have electrical conductivities significantly different from their surroundings. Spectral measurements (Armstrong et al., 1998; Suszcynsky et al., 1998) now confirm that significant ionisation is present in the early phase of sprite development, after initially indicating that this was not the case (Mende et al., 1995). The azimuthal lobe-structure expected from the scattering of transmissions from an assembly of such columns (Rodger et al., 1998) has been observed in the experimental data (Hardman et al., 1998). Taking the definition of a VLF sprite as a detectable VLF perturbation involving wide-angle scattering in the phase and/or amplitude of a transmission occurring simultaneous to a perturbation observed on at least one other VLF transmitter, a blind test was undertaken to test the association between VLF perturbations and red sprites. After identifying 24 VLF sprites, the timing was compared with red sprites observed in that period. All of these perturbations corresponded to optical red sprites, and only 1 (very faint) red sprite was noted during that night which was not associated with a VLF perturbation (Dowden et al., 1996b).

It has also been found that VLF sprites have an identifiable time signature — the perturbation decays logarithmically with time, not exponentially as expected and observed for classic Trimpi (Dowden et al., 1997). The characteristic logarithmic decay of VLF sprites has been explained in terms of scattering from a vertical column or set of columns extending from $\leqslant$ 50 to ~80 km altitude (Dowden and Rodger, 1997). Such columns decay from the bottom upwards, producing the logarithmic change in scattered signal. Various authors have attempted to use the properties of the VLF perturbations to infer information about the (electrical) nature of the red sprites. Calculations using a 3D-Born scattering code indicate that red sprite plasma is highly ionised (an excess of 4–5 orders of magnitude at some heights) in comparison with the ambient nighttime ionosphere in order to explain the observed strength of high-angle scattering (Rodger and Nunn, 1999) and logarithmic decay (Nunn and Rodger, 1999).

In contrast to the wide angle scattering described above there is a large body of evidence from the Stanford group that suggests that only lightning-associated ionospheric disturbances within 50 of the transmitter–receiver Great Circle Path will produce an early Trimpi (Inan et al., 1993, 1995a,b; Inan et al., 1996a,b,c; Johnson et al., 1999b). For example, it was reported that a "preliminary examination" of data from nine closely spaced (~65 km) VLF receivers, had not shown a single wide-angle scattering early Trimpi during the summers of 1997 and 1998 (Johnson et al., 1999b). In the cases examined, forward scattering patterns exhibit 15 dB beamwidths of less than 30° (i.e., scattering strongly along the transmitter–receiver GCP only). These cases were found to be consistent with a disturbed region in the lower ionosphere with an horizontal extent of 90±30 km (Johnson et al., 1999b). It appears that this group has observed only one example of wide-angle scattering in several years of operation and even this is thought to be coincidental (U.S. Inan, unpublished comment, URSI GA Toronto, 1999).

As noted above, the VLF sprites of Dowden and co-workers are strongly associated with red sprites, which are themselves strongly associated with large, positive cloud-to-ground (+CG) lightning discharges (positive CG discharges lower positive charge from the upper regions of the thundercloud to the Earth — see Section 2.1). This is, however, not the case with the early Trimpi events reported by Inan and co-workers. Using data from the United States National Lightning Detection Network (NLDN) (Wacker and Orville, 1999), which provides spatial and temporal information on CG lightning discharges in the continental USA, it was found that only 20% of early Trimpi events observed were found to be correlated with CG discharges (Inan et al., 1993), although all early Trimpi events had associated coincident VLF sferics. Early Trimpis which were CG correlated were regularly associated with negative CGs, and many of these discharges had low peak return currents, in some cases as small as 20 kA. To put this in perspective, more than 50% of all CG lightning discharges have peak currents > 20 kA (Ogawa, 1995). All earlier attempts to explain early Trimpi events relied on large electric field amplitudes from the lightning discharge (e.g., heating of ionospheric electrons by the VLF electromagnetic pulse (or EMP) from lightning (Inan et al., 1991)), and cannot explain such low thresholds. The data used by Inan et al. (1993) were collected in 1990, at which time the NLDN detection rate was estimated to be about 70–80%. It therefore seems likely that the "missing" early Trimpi associated discharges that produced detectable sferics were not CG lightning but rather cloud-to-cloud or intra-cloud (within the thunderstorm) discharges.

The suggested explanation for these observations relies on the effects on the ionosphere of the rapid decay (through lightning discharge) and slow-build up of thundercloud charges (Inan et al., 1996c). Quasi-electrostatic (QE) fields from the charged thundercloud are proposed to maintain the ionospheric electrons at a persistently heated level well above their ambient thermal energy. Changes in the thundercloud charge (those involved with lightning discharges) lead to heating or cooling above or below this level, and would be registered as sudden subionospheric VLF signal changes, occurring simultaneously with lightning discharges, and thus producing the onset of an early Trimpi. The recharging of the thunderstorm returns the ionospheric electrons to their previous levels and thus produces the decay of the observed perturbation. As the mechanism relies upon changes in the relative QE fields, discharges of either polarity or direction (CG or cloud-to-cloud) might produce a change in the lower ionospheric boundary sufficient to produce an observable VLF perturbation. Through this mechanism thundercloud charge changes associated with a 10 kA lightning discharge taking place over 10 ms (followed by cloud recharging) could lead to an early Trimpi (Inan et al., 1996c).

The observations of VLF sprites by Dowden and co-workers do not appear to contradict those of Inan and co-workers, as VLF sprites are thought to be produced by ionospheric changes with fine-structure (leading to wide-angle scattering) occurring over wide altitude ranges (leading to the logarithmic decay). As Dowden and co-workers have concerned themselves only with perturbation events that show wide-angle scattering (identified through multiple-receiver or transmitter experiments) or log decay, they would not be expected to observe perturbations of the type which would be produced through the QE heating mechanism. It is therefore possible that both mechanisms might be required to explain all the data. However, Inan and co-workers report they do not observe wide-angle scattering.

At this stage there appears to be only one set of observations in the literature independent of these two groups. Corcuff (1998) monitored the British transmitter GBR from a receiving point in France and compared observed perturbations with CG discharges collected by a lightning detection and location system. Over an observing period of ~1 h, 1084 negative CGs and 55 positive CGs occurred inside a ±50 km corridor around the transmitter–receiver GCP. A total of 6 perturbations were associated with simultaneous VLF sferics (thus the perturbations were early Trimpi), and none of these corresponded to negative CG discharges from the lightning detection system. One early Trimpi event was not associated with any CG discharge detected inside the corridor. All of the 5 remaining were associated with positive CG lightning. However, 3 of these 5 early Trimpi events on GBR occurred simultaneously with VLF perturbations on the French transmitter HWU (see Fig. 8), located at right-angles to the GBR-receiver GCP. These observations either suggest that the region of ionospheric modification is very large (> 350 km), or support wide-angle scattering as proposed by Dowden and co-workers. The two interpretations of early Trimpi perturbations have been subject to an exchange between the research groups (Dowden, 1996; Inan et al., 1996b), but this has not led to significant clarification. This is an area of active controversy.

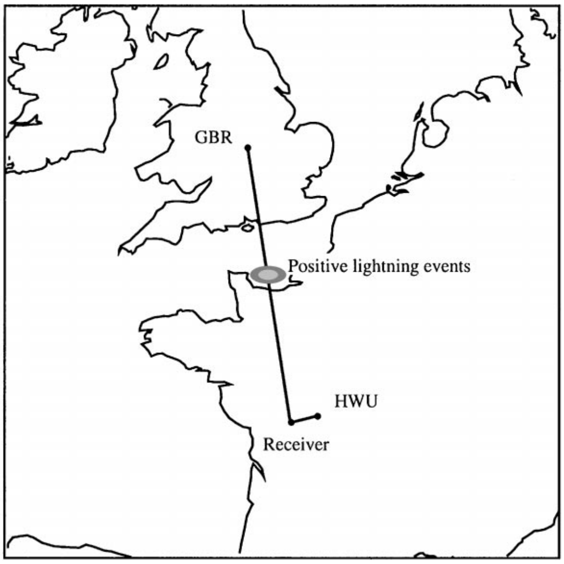

Fig. 8. Map showing the experimental set-up for the observations made by Corcuff (1998). The region of the English Channel in which positive CG discharges caused VLF perturbations on both GBR and HWU is shown shaded.

7.2.3. *Perturbations of VLF propagation by HF heating*

In recent years many powerful HF ionospheric heaters have been constructed which are capable of increasing the electron collisional frequency in the D region by an order of magnitude over an area of greater than 300 km^2 (Stubbe et al., 1982b; Gurevich and Migulin, 1982). These HF heaters have, for the first time, made it possible to study the effect of localized regions of perturbed ionosphere on the propagation of VLF waves in the Earth-ionsphere-waveguide. The first experiments (Jones et al., 1972) were made with the modest heater at Platteville, Colorado (50 MW ERP). Jones et al. (1972) observed small changes in both amplitude (~0.03 dB) and phase (0.3°) of 20 kHz signals reflected from the heated region. Barr et al. (1984), using the Max-Planck heating facility (300 MW ERP) near Tromsø, in Norway, were the first to make observations of a moveable ionospheric anomaly on VLF propagation. The effects were again small (±0.08 dB in amplitude and ±0.5° in phase) but clear diffraction effects, similar to those predicted theoretically by Wait (1964a) and Crombie (1964b), were observed on signals propagating to Skibøtn, Norway, from the Omega transmitter near Aldra, Norway. By repeating the experiment, during a period when the propagation from Aldra to Skibøtn was perturbed by significant modal interference, Barr et al. (1985b) observed peak amplitude and phase perturbations of 6 dB and 50°, respectively. They modelled their results using the propagation theory of Wait (1964a,b) updated to include multi-mode propagation in a waveguide formed between an anisotropic ionosphere and a finitely conducting ground. Dowden et al. (1991) repeated the experiments with similar results. However, in the analysis they separated the contributions of the direct and scattered signals to good effect, bringing added insight to the scattering process. The most recent work on the effects of HF heaters on VLF propagation was performed with the HIPAS heater facility in Alaska (Bell et al., 1995). They used superposed epoch and spectral analysis on the perturbed signals which they then studied with advanced waveguide propagation models (Poulsen et al., 1993a). The purpose of the study was to develop techniques for determining the characteristics of the ionosphere during operations of the HIPAS HF heater.

7.2.4. *Perturbations of VLF propagation by VLF heating*

Galejs (1972) was the first to suggest that VLF transmitters may cause significant ionospheric heating but it was more than 18 years before such an effect was observed experimentally. Inan (1990) observed modulation on the amplitude of the 24 kHz NAA transmitter near Maine, at Palmer Station, Antarctica, produced by the amplitude modulated NAU 28.5 kHz transmitter in Puerto Rico. After analyzing data from earlier HF and VLF heating experiments, Dowden and Adams (1991) concluded that, if the results of Inan (1990) were not instrumental in origin, then VLF heating must be more than 100 times more effective than HF heating. This conclusion was verified by Barr and Stubbe (1992). They found that the marked superiority of VLF heating was a feature of nocturnal ionospheres, VLF and HF heating producing similar effects in the daytime. They also found that HF heating maximized at high magnetic latitudes and that VLF heating maximized at low magnetic latitudes. In repeating Inan's experiment, Dowden and Adams (1992) found that signals from NWC in Western Australia, when received in Dunedin, New Zealand, appeared at times to exhibit the modulation of the Australian Omega transmitter. The Omega transmitter was located near the direct path from NWC to Dunedin. However, they were able to simulate the observed effect by injecting signals from a laboratory oscillator into their receiving system, casting doubt on their own and Inan's observations. A short time later further experimental evidence of the perturbation of the amplitude of VLF waves propagating in the Earth-ionosphere waveguide, by powerful VLF communications transmitters, was presented (Inan et al., 1992). The perturbations were small, typically ∼0.1 dB, but they were accurately modeled using a realistic 3-D model of sub-ionospheric propagation (Poulsen et al., 1993a). Larger amplitude (∼0.84 dB) and phase (5.3°) perturbations on VLF signals created by VLF 'heater' transmitters were also observed and they were found to be generally consistent with theoretical predictions (Rodriguez et al., 1994).

7.2.5. *Perturbation of VLF waves by earthquakes*

Perturbations in VLF phase and amplitude have been reported to occur before large earthquakes (Hayakawa and Fujinawa, 1994; Parrot et al., 1993; Parrot, 1995). The first study of this effect, reported in a Western journal, made use of the Omega navigation transmitters and claimed that 250 out of 350 earthquakes with magnitude M greater than 4 were associated with phase and/or amplitude variations (Gokhberg et al., 1989). However, a subsequent test of the link between these variations and earthquakes concluded that the observed precursory relationship was not statistically significant (Michael, 1996).

A recent approach to examining subionospheric signals for seismo-active effects was presented by Hayakawa et al. (1996) and applied to the "Kobe" earthquake ($M = 7.2$). These authors used signals from Omega Japan, observed at Inubo ∼1000 km away. The earthquake epicentre was located ∼70 km from the GCP. Hayakawa et al. (1996) considered the deviations of the terminator time (TT), defined as the time where a minimum occurs in the received phase (or amplitude) during sunrise and sunset. They noted that a few days before the earthquake the evening TT deviated significantly from the monthly average, exceeding the 2σ level derived from over 3 months of data. Simple theory suggested that the observed effect could be explained by decreasing the VLF reflection height by ∼0.7 km (Hayakawa et al., 1996), or ∼2 km (in the almost identical study by Molchanov et al., 1998). More realistic propagation models show that the changes in VLF reflection height associated with earthquakes would have to be considerably larger (∼4–11 km) to produce the observed TT changes (Rodger et al., 1999). The reported TT changes could be produced by alterations in the VLF reflection height commensurate with the effects of a solar flare, but this would lead to changes in received amplitude (or phase) that would be significant at all times, and not just during the day/night transition!

The TT method has since been applied to 10 other large ($M \geqslant 6.0$) earthquakes (Molchanov and Hayakawa, 1998). Five of these, all of which were reasonably shallow ($\leqslant$ 80 km) and occurred within 70 km of the GCP from Omega Japan to Inubo, were claimed to be associated with evening TT deviations.

However, significant doubt has recently been cast on the application of the TT method to earthquake prediction. Clilverd et al. (1999b) applied a simple statistical analysis to nearly 5 years of observations on the long (12 Mm) path from the north-eastern US to Faraday, Antarctica (65°S, 64°W). They found that the occurrence rate of successful earthquake predictions using the TT method could not be distinguished from that of chance. While this study had access only to long-path observations, it is the only report to date that has considered the statistical occurrence of TT changes in non-seismic periods.

7.3. *Theoretical studies of ELF/ VLF perturbations*

The initial impetus to the theoretical work on the effect of ionospheric perturbations on ELF and VLF radio-wave propagation can be traced to the early 1960s. Then many nuclear weapons had been detonated in the lower and upper atmosphere and there was a requirement to model the observations of how these explosions had affected the propagation of ELF and VLF radio waves (see Section 7.1.3). Two classical papers by Wait (1961, 1964b) and one by Crombie (1964b) written at this time, have formed the basis of all the later theoretical analyses of single-mode propagation in the Earth-ionosphere waveguide with perturbed boundaries. With the addition of the work of Lohrey and Kaiser (1979), who emphasized the contribution of modal interference, most of the significant physical components for an accurate waveguide model had been defined.

In his early model, which is now commonly termed a one-dimensional or 1-D model, Wait (1961) only considered changes of ionospheric height along the GCP between the transmitter and receiver. The ionosphere was considered infinite and homogeneous in the horizontal dimension transverse to the direction of propagation. However, this basic model, which in its simplest form supports only one mode of propagation, was used to analyze the results of many early papers on the Trimpi effect (Tolstoy, 1983; Inan et al., 1985; Inan and Carpenter, 1987). Inan and Carpenter (1987) recognized the need for more realistic three-dimensional models which included the effect of off GC path effects (see Crombie, 1964b; Wait, 1964b).

Dowden and Adams (1988,1989) developed a three-dimensional model based on "echoes" from LIEs located off the GC path. Their work, which had a stronger connection with the basic physics of the problem, was a useful development of the early work of Crombie (1964b). The same technique was also used successfully to analyze the perturbing effects, on the propagation of VLF radio waves in the Earth-ionosphere waveguide, of a heated patch of ionosphere (Dowden et al., 1991). Perturbations created by a patch of ionosphere, heated by HF waves, can be accurately modelled (Stubbe and Kopka, 1977). Perturbations created by HF heating also have the advantage that they can be scanned across the ionosphere merely by deflecting the HF beam. Barr et al. (1985b) modelled the effect of perturbations produced by HF heaters with some success. They used an Earth-ionosphere waveguide program that allowed for ionospheric anisotropy, the effect of the Earth's curvature and finite ground conductivity. The effect of off GC path disturbances was accounted for using the theory developed by Wait (1964b) and multiple modes were included in the analysis. The inclusion of multimode propagation allowed Barr et al. (1985b) to model the effects of enhanced amplitude ($\sim$6 dB) and phase ($\sim 50^\circ$) perturbations, created by modal interference, which had been observed during the course of their experiments.

In working to derive a more quantitative analysis of LIEs produced by whistlers, Poulsen et al. (1990) also independently developed sophisticated waveguide propagation programs. They used the "MODEFNDR" programs (Morfitt and Shellman, 1976; Shellman, 1986; Ferguson and Snyder, 1987) developed by the US Naval Ocean Systems Center (NOSC) to solve the waveguide modal equation and the work of Wait (1964b) to account for the effects of LIEs located off the GC path. This initial work was limited to one mode of propagation but was later extended to give full multi-mode solutions (Poulsen et al., 1993a). However, mode conversion due to scattering at the LIE was not included. They also extended their work to study the contributions of conductivity and permittivity of the ground in the vicinity of the ionospheric perturbation (Poulsen et al., 1993b). They concluded that, except for areas of very low conductivity such as glacial icecaps, scattering was largely independent of ground parameters. The effects of mode conversion were studied by Wait (1995), for the special case of a column of ionization in the Earth-ionosphere waveguide, and he found significant mode conversion where the ionization was a function of altitude.

Although designed with Trimpi studies in mind, the computer program developed by Poulsen et al. (1993a) has recently been used to analyze the effect of ionospheric anomalies, produced by the HIPAS HF heater facility in Alaska (Bell et al., 1995). This experiment was similar to that of Barr et al. (1985b) in Tromsø and provided confirmation of the theoretical and experimental techniques used at both heater facilities.

Nunn (1997) has adopted a slightly more rigorous approach to Trimpi modelling based on a multi-modal treatment of an assembly of point scatterers, although the work is still subject to the Born weak scattering approximation. We believe the modeling of VLF perturbations produced by LIEs has probably now reached the stage where any uncertainties produced by inadequacies in the theory are negligible compared to the variability and uncertainties in the spatial structure and intensity of the ionization patches themselves. This belief is supported by recent ray tracing work by Strangeways (1999) who has deduced that LIE dimensions may be much larger than suggested from whistler duct width measurements. He suggests it may be more appropriate to model Trimpis with larger ionization patches, up to 300 km, as estimated experimentally, that will then require smaller and more realistic enhancements of electron density in the ducts to model the experimental data accurately.

8. Alpha and Omega

A review of VLF radio-wave propagation research for the last 50 years of the 20th century would not be complete without a mention of the VLF global navigational systems, Alpha and Omega.

Whereas the Omega system was an international facility, under the control of a number of independent states, the Alpha system was operated and controlled solely by the USSR (Peterson, 1990). Unlike Omega, the Alpha system operated in relative obscurity but it has been studied by a number of workers, including John Beukers, who was probably the first to use the term VLF ALPHA to describe the Soviet system (see references in Peterson, 1990). Alpha started implementation in 1962 and reached full operational capability by 1973. The system had transmitters in Krasnodar, Novosibirsk and Komsomalskamur. Alpha usually operated on frequencies of 11.905, 12.649 and 14.881 kHz with a 3.6 s switching cycle of 6 equally spaced 400 ms transmission segments. An alternate set of 3 frequencies was also occasionally used. The transmitters were estimated to radiate 50 kW compared to the 10 kW transmitters of the Omega system (Peterson, 1990).

According to John Alvin Pierce, the inventor of Omega, the breakthrough in the development of Omega came in 1953 with the visit to Harvard of Dr Louis Essen, of the National Physical Laboratory, England. Essen was an expert on frequency control and suggested that Pierce should try to detect signals in Massachusetts from the 60 kHz transmitter MSF located near Rugby, England. It was the phase stability of these long-path transmissions, initially used for frequency and time comparisons over long distances, which led Pierce to develop the Omega navigation system (Pierce, 1989). Initially the system, called Radux-Omega, radiated in the LF and VLF band (Swanson, 1983) but the LF component was later rejected leaving only VLF transmissions on 10.2 kHz.

Modern transmissions began in 1966 with transmitters in Norway, Trinidad, Hawaii and Forestport, New York. In earlier transmissions the system was synchronized using a master–slave technique but in the modern configuration each transmitter was locked to its own bank of caesium frequency standards. The system was placed on an interim operational status in 1968. The final system, with 8 transmitters, came into operation in 1982 with the construction of Omega Australia. Each station radiated omni-directional, time-multiplexed transmissions of 10.2, 11.05, 11.33, and 13.6 kHz and one additional frequency unique to each station. The completed system provided global navigation with an accuracy of about 1 nautical mile (Swanson, 1982). The system continued in service until switched off at 0300 UT, 30 September 1997, its global navigational function having been superceded by the more accurate satellite based Global Positioning System. In its 30 years lifetime Omega not only provided a cheap global navigational aid but also a source of VLF signals for global ionospheric research, as many of the papers listed in this review testify. An excellent source of reference for Omega related research is provided in the *Bibliography of Omega Publications*, published by the International Omega Association (IOA 1991).

As the lifetime of Omega has spanned most of the 50 years of publication of the Journal of Atmospheric and (Solar-) Terrestrial Physics, it is appropriate that it should be the last topic of this review. It will be interesting to see if the study of ELF and VLF radio waves continues to be a productive area of research during the next 50 years.

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