50 Years of Schumann Resonance

Kristian Schlegel[1] and Martin Füllekrug[2]

[1] Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany

[2] Department of Electronic and Electrical Engineering, University of Bath, UK

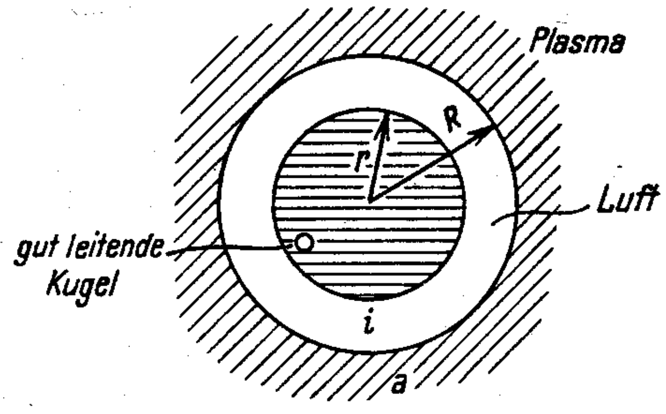
(originally published in *Physik in unserer Zeit*, 33(6), 256-26, 2002. Translation: Catarina Geoghan, 2007)

In 1952 Winfried Otto Schumann, at that time Director of the Electrophysical Institute at the Technical University of Munich, published his first paper about electromagnetic waves in the waveguide which is formed by the earth's surface and the ionosphere. Since this time the study of these, later referred to as Schumann resonance waves, has become an interesting subject for research. With modern measurement techniques the recording of these resonances opens up various application possibilities, ranging from global lightning triangulation, detection of space weather effects to tracking down global climate variations.

1. Schumann Resonance Principles

Each finite waveguide has its characteristic natural frequency (resonant frequency). Schumann (see box 1) recognised for the first time, that the space bounded by the highly conducting earth and the likewise highly conducting ionosphere represents such a waveguide (fig. 1).

Fig.1: Original sketch by Schumann [1] for the illustration of the waveguide which is formed by the highly conducting earth and the highly conducting ionosphere (plasma), r signifies the earth radius, R-r ≈ 80 km.



One can derive its resonant frequency approximately from the assumption that the resonance wavelength must be an integer part of the circumference of the earth. With this assumption one arrives at:

$$f_n = \frac{c}{\lambda_n} = \frac{c}{2\pi r_e} n \approx 7.5n\,[Hz] \qquad (1)$$

n=1 represents thereby the fundamental frequency, all larger n the higher harmonic waves.

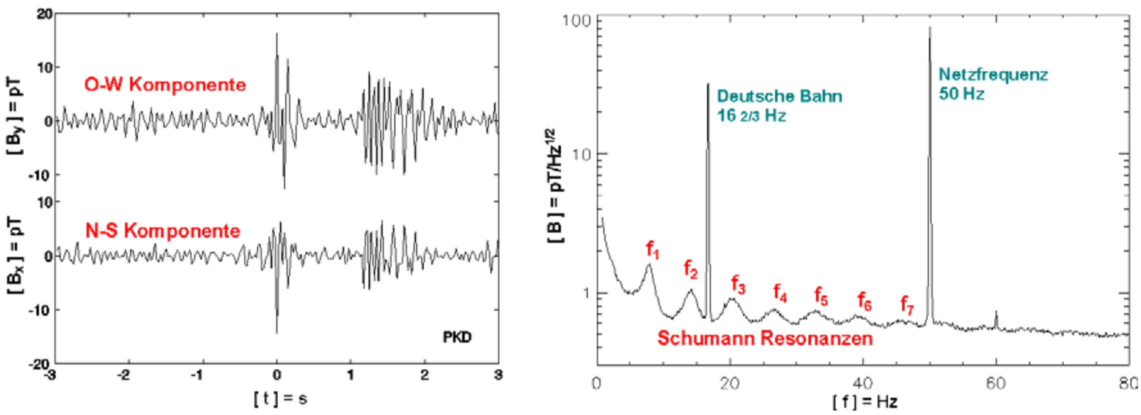
Schumann's contribution consisted of the fact that he derived the eigen frequencies of this waveguide mathematically in a very general form [1]. Taking spherical geometry into account one obtains the resonant frequencies

$$f_n = \frac{V(\sigma)}{2\pi r_e}\sqrt{n(n+1)} \approx 6.0\sqrt{n(n+1)}\,[Hz] \qquad (2)$$

which also includes the damping of the waves because of the finite conductivity of the 'upper' boundary of the waveguide, namely the ionospheric D-layer. Its propagation speed V therefore amounts to - depending on the conductivity σ - about 80% of the speed of light (the relationship with the conductivity is described in somewhat more detail in box 2). While the conductivity of the ionospheric lower boundary is very variable at a height of 70-90 km with values between 10^{-5} to 10^{-3} S/m (see below), the average conductivity of the ground and the sea at approximately 10^{-3} S/m is practically constant and usually greater than the latter. It therefore does not contribute substantially to the damping of the waves.

Schumann, who had for some years also dealt with so-called sferics, the electromagnetic emissions of lightning, recognised also that it is these impulse-like emissions which excite oscillations in the earth-ionosphere waveguide. Fig. 2 shows the time signal of these oscillations together with their spectrum for all modes up to n=7.

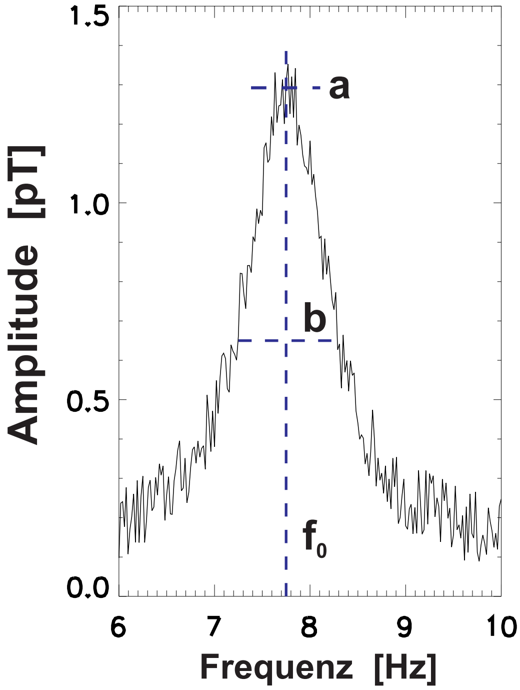
Fig. 2: Time signal (left) and spectrum (right) of the first 7 Schumann resonances measured at Silberborn in Solling Mountains (Germany).



Although the nearest electric railway is about 30 km away, the 16 2/3 Hz and the mains frequency signals are much stronger than the Schumann resonance. The increase in the spectrum at frequencies <5 Hz is caused by so-called magnetic micropulsations which originate in the earth's magnetosphere.

The spectrum for each mode can be characterised by three values: its centre frequency, its amplitude and its width (fig. 3), the latter is a measure of the damping of the mode in question.

Fig. 3: The spectrum for each mode (here for n=1) can be identified by the three parameters Centre Frequency f_0, Amplitude a and Width b.



The first measurements were published by Schumann and König in 1954 [3]. Between 1960 and 1970 further measurement results were published as well as extended theoretical work on the topic. Schumann resonance experienced a renaissance at the beginning of the 1990's, after measurement methods had improved and new applications appeared (see overview in [4]).

2. Measurement Methods

Since Schumann resonances involve electromagnetic waves, the electrical and/ or the magnetic components can in principle be recorded. With the electrical component the potential between earth and a dish or ball mounted at a height of a few meters is measured as a function of time. Since the atmosphere exhibits very high impedance of the order of magnitude of 10^{14} Ω, the measuring amplifiers must be of extremely high impedance, but also at the same time fulfil the necessary frequency bandwidth of some 10 Hz. For the measurement of magnetic components induction coils are used, which are set up horizontally in two directions perpendicular to each other (N-S, E-W), in order to also include the polarisation of the waves (see fig. 2). Since the signal is of the order of magnitude of 0.001-1 pT (10^{-12} Tesla), coils with a core of high permeability as well as several 10000 turns are necessary. The measurement of the electrical component proved very error-prone because of charging of the ball/dish through the photoelectric effect or surface contamination, magnetic field measurement is therefore preferred nowadays. Measurement in industrialised areas is however always difficult, because of the interference with the 50 Hz mains frequency and the 16 2/3 Hz of the German railway, even at a greater distance of such sources (fig. 2). Narrow-band filters can thereby not be used because of the inevitable distortion of the wanted signal. Recording electronics must therefore cover a great dynamic range, in order to be able to eliminate the interference computationally. Clean measurements can be obtained, for instance, from stations in the Antarctic. Fig. 4 shows a coil as well as the appropriate electronics for measurements in the field.

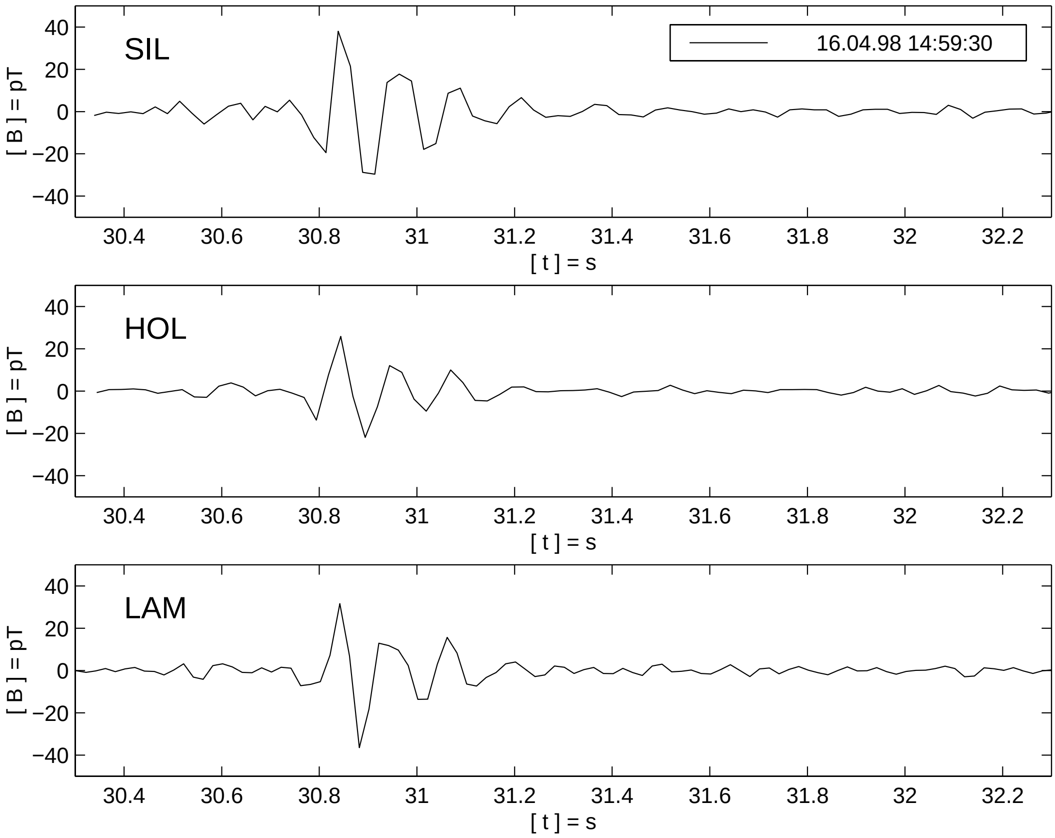
Fig. 4: Vertically placed coil for the measurement of the vertical component of the Schumann resonance (above) and electronics box for the detection and storage of the time signal (below). Because Schumann resonance must be measured far away from technical disturbances, the entire electronics is operated in the open with batteries.

3. Schumann resonance Applications and Effects

a. Lightning Detection

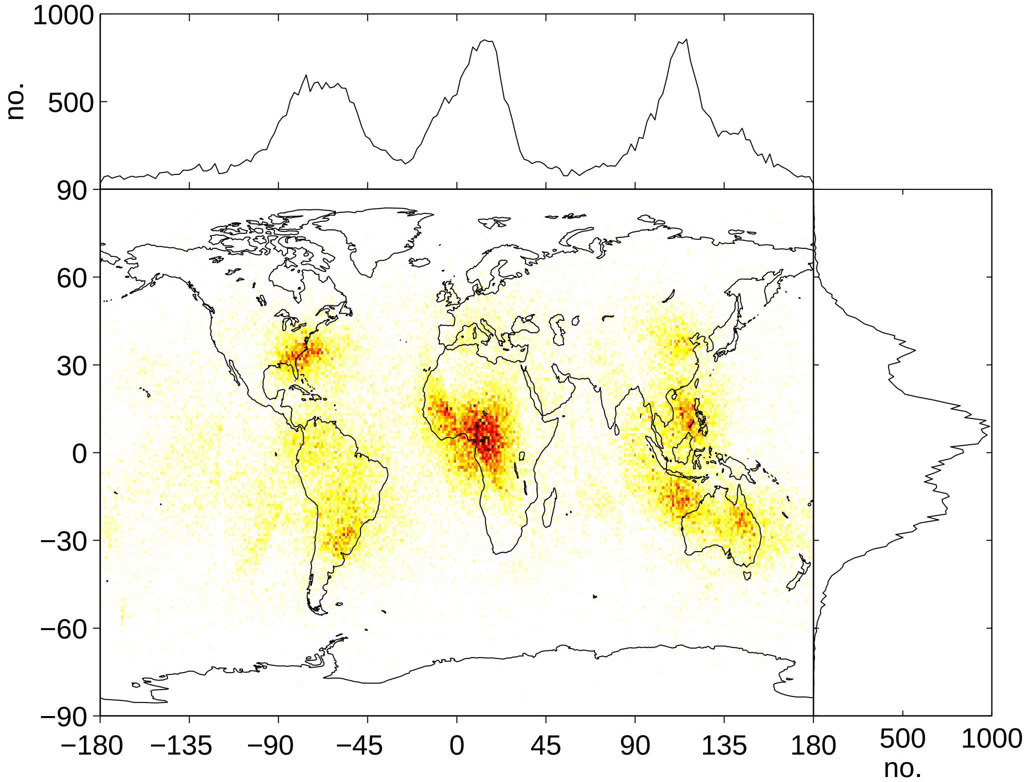
A field of application of Schumann resonance, which was already recognised very early, is global lightning triangulation. Since each lightning induces oscillations in the earth-ionosphere waveguide, three stations are in principle sufficient, which should be at as large a distance as possible from each other. Thereby, the time signal of these oscillations are recorded with corresponding high time resolution (approx. 1/100s) (fig. 5).

Fig. 5: Concurrent recording of the first Schumann resonance in Hollister/California (HOL), Silberborn/Germany (SIL) and Wellington/New Zealand (WEL). The triangulation showed that the flash, which released this signal, ignited over South America.



Temporal synchronisation of the stations is ensured with the aid of GPS satellites. Through cross-correlation of these three time series, lightning can then be located with an accuracy of several 100 km with the aid of spherical geometry. Fig.6, for instance, shows the result of such measurements for one month, which can be used for the study of global thunderstorm activity [5]. A global network for monitoring of lightning is being developed as a warning system for air traffic.

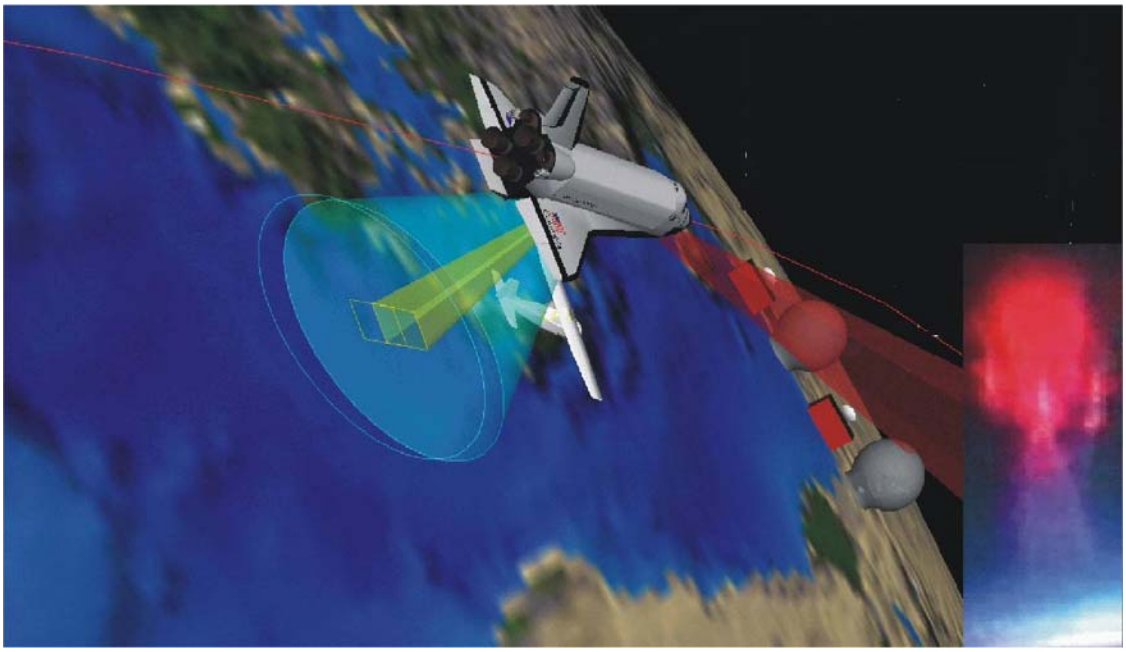
Fig. 6: The global distribution of flash frequency in April 1998 recorded with the help of Schumann resonance triangulation. There are generally three centres with increased flash frequency: over America, Africa and Southeast Asia, while only few thunderstorms appear over the oceans.



In the last few years these methods have also been used together with optical measurements for the observation of sprites. Sprites (see fig. 7 right) are transient, red-bluish light phenomena, which reach up from the top surface of the cloud to the ionosphere. These optical emissions were first discovered in 1989 [6] and are induced by unusually strong lightning. The electromagnetic impulse of such lightning leads, in addition, to circular light phenomena in the ionosphere, which are referred to as elves. Besides sprites, blue jets have also been observed. These are relatively narrow, blue rays of light, which reach up from the thundercloud to 40-50 km. Despite intensive research it has not so far been unequivocally clarified whether these phenomena really are a question of natural gas discharges in the atmosphere. However, there has been a report in Nature [7] about a bright flash over an oceanic thunderstorm up to the ionosphere near Puerto Rico. The luminosity of this phenomenon is very suggestive of an electrical short-circuit between the troposphere and the ionosphere.

In the framework of the space shuttle mission STS-107, the first Israeli astronaut in space will use a video camera for the determination of the global frequency of this recently discovered lightning in the mesosphere in the summer of 2002 (fig. 7).

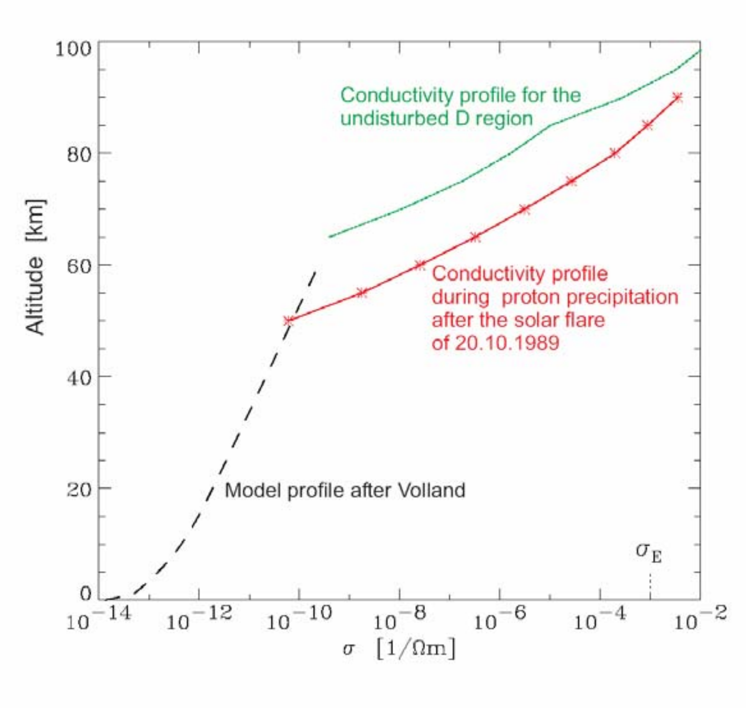
Fig. 7: From the space shuttle an Israeli astronaut will search for sprites and natural gas discharges in the mesosphere with a video camera. On the right below the original photo of a sprite is inserted (the picture was created with STK Software. With approval of M. Moalem, IAF).



b. Global D-layer Monitoring and Space Weather

As previously mentioned, the conductivity of the lower boundary of the ionosphere is very variable. It is ultimately determined by the electron density and the collision frequency between neutral particles and electrons within the ionospheric D-layer. The electron density changes regularly with the position of the sun, i.e. with the time of day and season, the collision frequency is proportional to the pressure in this height region, which likewise is subject to seasonal variation. In addition, there are irregular changes. During geomagnetic storms, electrons from the magnetosphere with energies of some keV are precipitating into the ionosphere and cause additional ionisation, whereby electron density can rise by more than an order of magnitude above normal values. Even stronger changes are caused by solar flares, as a result of which protons are emitted with energies of over 100 MeV. These particles can penetrate deeply into the atmosphere and cause additional ionisation down to a height of 50 km. As a result the conductivity is not only significantly increased, but the upper boundary of the waveguide is also shifted far downward (fig. 8).

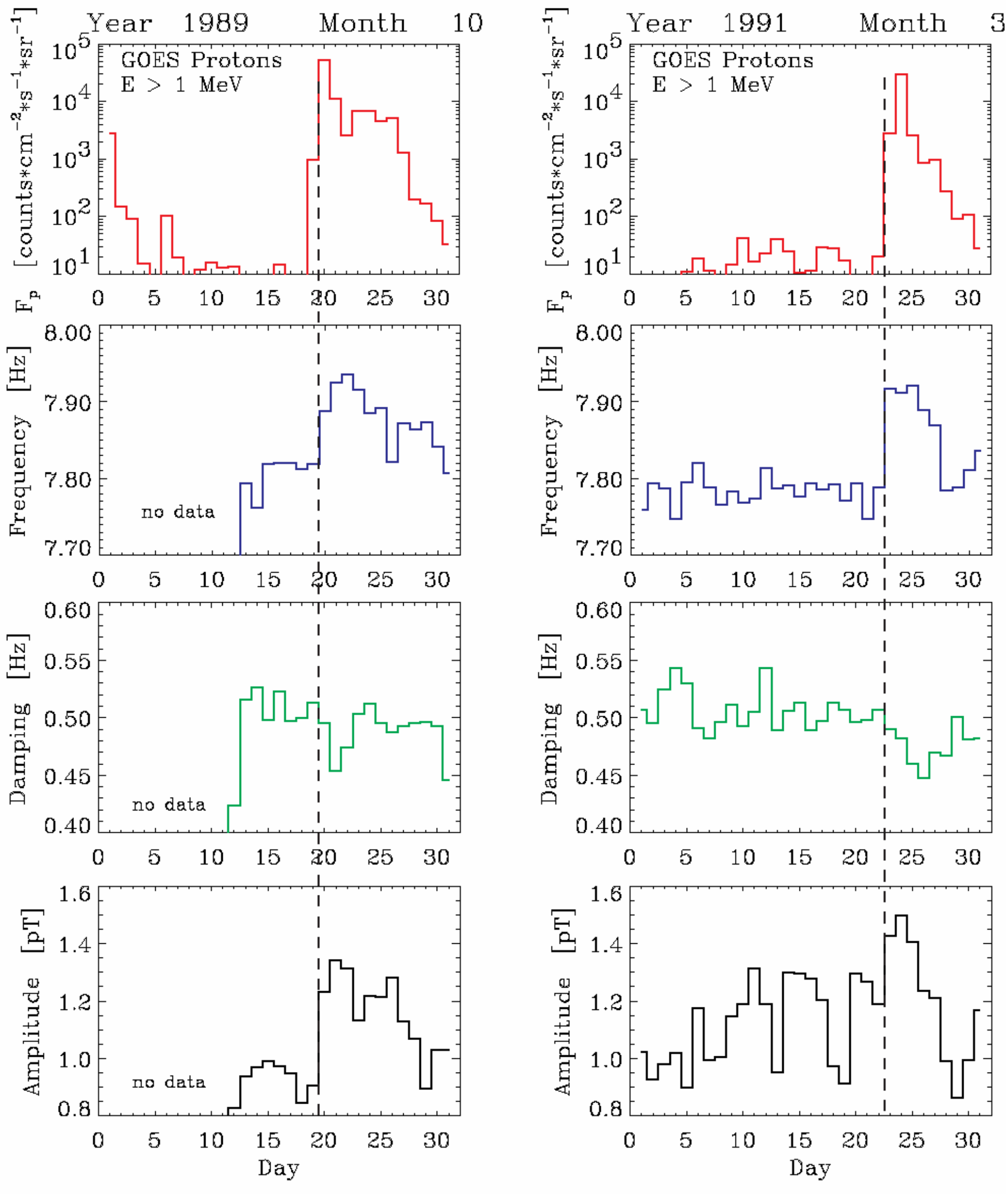
Fig. 8: Conductivity of the ionospheric D-layer under normal conditions and after a solar flare. The raised conductivity changes not only the electric properties of the earth-ionosphere waveguide and thereby the Schumann resonance parameters, the upper boundary of the waveguide is also shifted downwards substantially by such events [9].



Such space weather events affect all three parameters of the Schumann resonance spectra in clearly measurable ways (fig. 9).

These parameters can therefore be used in order to monitor the temporal variation in the D-layer conductivity, which Schumann already referred to in his second publication on this topic [2]. Naturally, in this way one arrives at a global average value, which is to be interpreted as a mean between the dayside and the nightside of the earth. A recording of this mean conductivity is nevertheless meaningful since, apart from regular seasonal variation, the above mentioned irregular deviations can also be recorded in a simple manner. Such monitoring of the D-layer is already possible with a single station in an interference-free environment [8] and a global tomography of the ionosphere becomes possible with a network of stations.

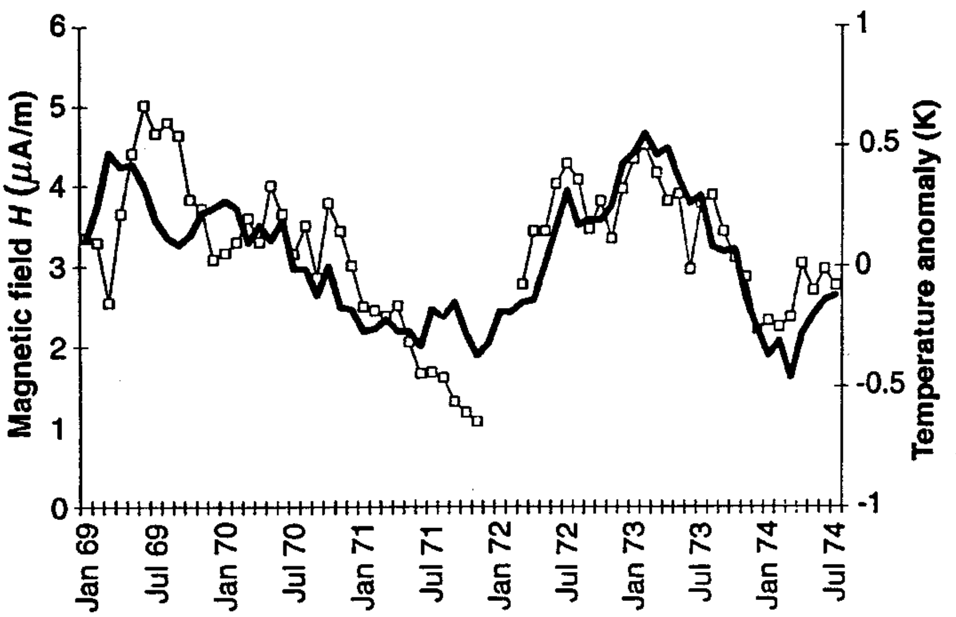
Fig. 9: Changes in Schumann resonance parameters f_0, b, a (cf. fig. 3) after two solar flares from 20.10.1989 (left) and from 22.3.1991 (right). Directly above the flux of high-energy protons is shown, which cause the additional ionisation below 80 km and thereby change the conductivity as shown in fig. 8 [9].



c. Climate Change

Schumann resonance is possibly suitable as a sensitive thermometer for global temperature changes. Global thunderstorm activity is essentially determined by meteorological factors, among other things by the temperature of the equatorial troposphere. On the other hand, Schumann resonance allows for the quantitative measurement of global thunderstorm activity, as pointed out above. In a sensational and exciting paper the American meteorologist E. Williams has published a comparison between the relative tropical temperatures during an El-Nino cycle and the amplitude of the first Schumann resonance, whereby a significant positive correlation was found [10]. Although his data covers only a period of 5 1/2 years (fig. 10), these results are very promising for the understanding of long-term climate variations. A possible non-linear reinforcement of the greenhouse effect is thereby of special interest. It is well-known that global thunderstorm activity in the tropics transports large quantities of water vapour into the tropopause. Water vapour is, however, also the most important greenhouse gas. Therefore, the technically difficult measurement of the water vapour content in the tropopause can be realised with the help of Schumann resonance [11] and contribute to current questions in climate research.

Fig. 10: The amplitude of the first Schumann resonance and relative change in the tropical surface temperature (thick line). From [10].



d. Biological Effects

Schumann himself was interested in the biological effects of sferics in general, and his student and later colleague Herbert König has continued this work. In a summary [12] the latter quotes many surprising results of such effects. They span from an influence on yeast cells and bacteria as well as plants and animals to humans. Human weather sensitivity is, for example, strengthened with increased amplitudes of natural oscillations at 10 Hz. With artificial application of such waves human circadian periodicity is significantly accelerated, test subjects show extended response time, or they cause headache. In many of these experiments effects showed a strong dependence on frequency. The so-called alpha waves during brain activity lie in the same frequency range as the first two modes of the Schumann resonance. Medics speculate that this is possibly no coincidence, but human adaptation to the electromagnetic environment in the course of evolution. In this border area between physics, biology and medicine there are perhaps still interesting results forthcoming.

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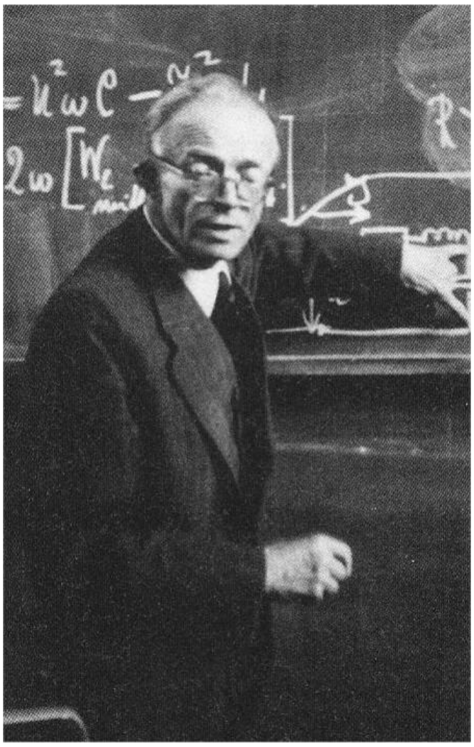
Box 1

W.O. Schumann

Born on 20th of May 1888 in Tübingen, Winfried Otto Schumann spent his childhood and youth in Kassel, Bernsdorf near Vienna and Karolinental near Prague. After studying electrical engineering at the Technical College in Karlsruhe, and his doctorate (1912) on a subject of high-current technology, he worked as a manager at the High Voltage Laboratory at the Bown, Boveri and Cie Company up to the outbreak of the First World War. In 1920 Schumann qualified as a professor (Habilitation) at the Technical University in Stuttgart where he was employed as a research assistant. Immediately afterwards he was offered a position as a university professor of physics at the University of Jena. In 1924 he took up an offer as full professor and director of the newly established Electrophysical Laboratory at the Technical University of Munich. This was later upgraded to the Electrophysical Institute, and he remained there until his retirement in 1961. He practised his teaching, however, up to his 75th year. Schumann died at the age of 86 years on 22nd of September in 1974.

While during his industrial activity he had dealt primarily with the disruptive field strength of gases, liquids and solid states, during his time in Munich his interest extended to high-frequency technology and plasma physics. In a series of very noteworthy publications Schumann worked on the behaviour of the ionosphere and plasma experiments in the laboratory under similar conditions.



In a third productive period after 1950, Schumann dealt with questions of wave propagation and with electromagnetic waves which are induced by lightning. During this time the publications focussed on the resonances named after him.

Schumann was respected both by colleagues as well as by students as an excellent academic teacher. His listeners were inspired by the master of the art of lecturing, the lectures distinguished themselves by exemplary descriptiveness and clarity, but at the same time were performed with wit and humour.

W.O. Schumann during his popular lecture.

Box 2

The propagation velocity of the waves in the cavity between Earth and the ionosphere used in eq. (2) is V=c/n, where the complex index of refraction can be written in a first approximation as

$$n = \sqrt{1 + i\frac{c\Delta_i}{\omega h_1}} \qquad \text{(A1)}$$

Here Δ_i is the inverse index of refraction of the ionosphere, for which in the simplest description a lower boundary at a fixed height h_1 (about 70-80 km) is assumed; c is the velocity of light. The relationship between this inverse index of refraction and the conductivity of the ionosphere σ_0 is given as

$$\Delta_i = \left(1 + i\frac{\sigma_0}{\varepsilon_0 \omega}\right)^{-1/2} \qquad \text{(A2)}$$

The surface of the Earth is assumed in this case as a perfect conductor.

In a more realistic description instead of the constant conductivity σ_0 a conductivity profile is used which is characterised either by one or by two scale heights (S_1, S_2). In the 2-scale-height model, instead of (A1) the index of refraction becomes

$$n = \sqrt{\frac{h_2(\omega) - i\frac{\pi}{2}S_2}{h_1(\omega) - i\frac{\pi}{2}S_1}}\,, \qquad \text{(A3)}$$

where we assume that the conductivity profile is described at height h_1 by the scale height S_1, and at height h_2 by the scale height S_2. The so-called conductivity boundary h_1 is approximately located at an altitude of 50 km, the reflection boundary h_2 at 75 to 85 km depending on the actual electron density profile of the ionosphere (c.f. fig. 8). Since the complex index of refraction (A1,A3) depends on the wave frequency ω, the centre frequency and the width of the spectrum (damping) are in turn related to the conductivity. This explains the results shown in fig. 9. A detailed derivation of the above expressions is documented in [4].