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Modern Research on the Schumann Resonances

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In 1952, W.O. Schumann unexpectedly published a series of works on the Earth-ionosphere cavity (Schumann 1952a, b, c). He opened a new field of geophysical research, focusing on the issues of ELF wave propagation in the Earth-ionosphere waveguide. The cavity considered by Schumann was idealised; it consisted of two concentric perfectly conductive spherical surfaces, spaced by the "height of the ionosphere" h. Schumann's solutions showed that the resonance frequencies of the cavity are practically independent of h and are given by the equation $f_n = 7.49\ (n\ (n + 1))^{1/2}$, which gives the first modes: 10.6, 18.4, 26.0, 33.5, 41.1,... Hz. The first attempt to observe resonances of atmospheric noise carried out in Munich failed (Schumann and König 1954).

Schumann's publications were soon noticed and generated a considerable interest. Most of the works in the initial period were of an academic nature, but the Pangloss research program launched in 1959 by the US Navy focused mainstream research within its framework. The main goal of the military program was an artificial generation of Schumann resonances, with the aim to build a global communication system (Wait 1972, 1977). Before the system for generation of artificial waves was developed, M. Balser and C.A. Wagner from MIT (Massachusetts Institute of Technology) carried out the first successful observation of natural Schumann resonance field (Balser and Wagner 1960). This confirmed the opinion that the noise generated by atmospheric discharges is sufficient for the Schumann resonance studies (Balser and Wagner 1962, Pierce 1963, Blackband 1964, Rycroft 1965, Polk 1969). A significant deviation of the observed resonance frequencies of the cavity: 8, 14, 20, 26, 32, ... Hz from those anticipated by Schumann required modelling of the cavity considering the influence of the ionosphere. Soon, the first models of ELF wave propagation in the ground-ionosphere waveguide were created. They were taking into account the dispersive nature of losses caused by a conductive ionosphere (Galejs 1961, Wait 1962). A simple exponentially increasing vertical profiles of ionospheric conductivity improved the accuracy of modelling of the cavity to such extent that the quality factors and resonance frequencies became close to those observed (Row 1962, Wait 1962, Jones 1964, Chapman and Jones 1964, Galejs 1965, Rycroft 1965). The use of more realistic aeronomical conductivity profiles of the ionosphere contributed to further improvement of the Earth-ionosphere cavity model (Madden and Thompson 1965, Jones 1967, Galejs 1970, Booker and Lefeuvre 1977, Tran and Polk 1979, Bliokh *et al.* 1980).

The work of Madden and Thompson (1965) also opens a new stage of the modelling of the ground-ionosphere waveguide in the ELF range. Due to the low height of the ionosphere compared with the wavelength of ELF waves in the cavity, the authors proposed the adoption of the TDTE (Two-Dimensional Telegraph Equations) model in the form of the two-dimensional spherical transmission line in which Maxwell 3D field equations are replaced with telegraph equations for voltages and currents. In the Madden and Thompson transmission line, the distance h between the ground and the ionosphere is constant and does not depend on the frequency.

In the nineteen seventies, as part of the Sanguine project, the first propagation measurements were carried out on continental paths (Bernstein *et al*. 1974, Wait 1972, 1977). Broadband quasi-orthogonal grounded antennas having the lengths of several dozen kilometers were used in this research. As a result of measurements conducted in the 40–80 Hz range, the frequency 76 Hz was selected as an optimal operating frequency for the future global Seafarer system intended for communications with submarines, and the measured ground-ionosphere waveguide attenuation rate at this frequency was determined to be 1.2 dB/Mm during the day and 0.8 dB/Mm during the night (Bannister 1975, Burrows 1978).

At the end of the nineteen seventies, C. and P. Greifinger (Greifinger and Greifinger 1978, 1979) made a breakthrough in the ground-ionosphere waveguide modelling. Analyzing the mechanisms of penetration of the electric and magnetic field components of the EM waves into the ionosphere, they introduced two different characteristic heights of the waveguide: the electric height h_e and the magnetic height h_m. They introduced simple relationships between the height ratio and the phase velocity and attenuation coefficient in the waveguide. This idea was used in Sentman’s works on the two-height Earth-ionosphere cavity (Sentman 1990, 1996). Soon after, Kirillov (Kirillov 1993, Kirillov *et al.* 1997, Kirillov and Kopeykin 2002) noted that the characteristic heights described by the Greifingers h_e and h_m are closely related to the unit parameters L and C of the two-dimensional transmission line introduced by Madden and Thompson (1965). Over the next few years a number of publications focused on the modelling of characteristic heights h_e and h_m versus the frequency, using different ionospheric conductivity profiles. The characteristic heights became the basic parameters of the ground-ionosphere waveguide, allowing for solving any propagation problems and resonance phenomena in the ground-ionosphere cavity in the ELF range (Kirillov *et al.* 1997, Mushtak and Williams 2002, Williams *et al.* 2006, Pechony and Price 2004, Kulak and Mlynarczyk 2013, Kulak *et al.* 2013, Galuk *et al*. 2015).

Over the years, the number of Schumann resonance observatories was growing. The ELF waves in the ground-ionosphere waveguide are quasi-orthogonal (q-TEM), the polarization of the electrical component is vertical, and the two independent orthogonal magnetic components are horizontal, parallel to the ground. Therefore, the observation of the electrical component is carried out using short vertical dipoles, and the magnetic components are recorded with a pair of perpendicular magnetic loop antennas or ferrite antennas (Ogawa *et al.* 1966). Sometimes a full set of antennas is used to measure orthogonal components, which enables observations of Schumann resonances using the Poynting vector spectrum (Belyaev *et al.* 1999). Observational publications focus on measurements of Schumann resonance parameters, their variability and its causes (e.g. Balser and Wagner 1962, Ogawa *et al.* 1968, Polk and Toomey 1972, Nickolaenko and Rabinowicz 1995, Nickolaenko 1997, Nickolaenko *et al*. 1998, Sátori 1996, Neska and Sátori 2006, Greenberg and Price 2007). The amplitudes and frequencies of individual resonance modes are studied in function of time and spatial distribution of atmospheric discharges. In individual observatories there are significant daily fluctuations of resonance frequencies, reaching up to 0.5 Hz in the case of the first mode. The difference in the resonance amplitudes observed simultaneously on the day and night side of the cavity was noticed as well (Sentman and Fraser 1991).

The effect of the disturbance of the upper ionospheric layers on the state of the cavity, caused by rapid increase in the solar activity was analysed (Blackband 1964, Cannon and Rycroft 1982, Magunia 1996). Long-term changes in the cavity parameters were also analyzed over time intervals covering the 11-year cycle of solar activity (Kulak *et al.* 2003b, Sátori *et al.* 2005). The view was established that UV and X radiation reaching the ionospheric D layer and increasing its ionization, increases the modal resonant frequencies and the quality factor of the cavity. In turn, sporadic streams of high-energy protons reaching the ionospheric layer C (about 35 km) have the opposite effect (Schlegel and Füllekrug 1999, Roldugin *et al.* 2001). The effects of various types of ionospheric disturbances on Schumann resonances were also considered theoretically (Galejs 1972, Sentman 1983, Füllekrug 2000, Füllekrug *et al.* 2002). A current review of the work concerning the impact of high-energy solar emissions on the Earth-ionosphere cavity can be found in Williams and Sátori (2007) and Sátori *et al.* (2016).

The discovery of strong influence of the temperature variations in the atmosphere of the tropical zone on the amplitude of the 1st Schumann resonance mode made by Williams (1992), opened new possibilities for accurate climate monitoring (Rycroft *et al.* 2000). Research on reconstruction of global storm activity based on Schumann resonance spectra was conducted before as well. Simplified analytical solutions based on the method of variable separation were used for this purpose, describing the resonance component of the field in the cavity (Galejs 1972). These frequency solutions are characteristic for the source-observer distance, which enabled using them as a source distance indicator. Inverse solutions rely on the search for the analytical spectrum that is closest to the observational spectrum and on this basis determining the distance of the observer from the storm center and determining its intensity (Clayton and Polk 1977, Polk and Toomey 1972, Heckman *et al.* 1998, Nickolaenko and Rabinowicz 1995, Nickolaenko *et al.* 1998, Shvets 2001, Yang *et al.* 2009).

Analysis of strict solutions for inhomogeneous field equations, which take into account the space-time mechanism of filling the cavity by a point source, reveals that there are significant deviations of the real distribution of fields in the cavity from a simplified solution obtained by separation of variables (Kulak *et al.* 2003a). These differences are caused by the waves propagating directly from the source, before they form a resonance field as a result of interference of waves propagating around the globe. Strict solutions have fully explained why significant changes in the observed Schumann resonance frequencies depend on the observer-source distance. For example, in the case of the first mode, observers located close to the source record spectra with lower Schumann resonance frequencies, much lower than the resonance frequencies of the cavity.

The application of full solutions to solving inverse problems opened a new stage in research on the distribution of sources and measurements of cavity parameters. Thanks to the accuracy of the new method, it was possible to measure the parameters of the cavity during an 11-year solar activity cycle and analytically link the resonance frequencies of the cavity with the Wolf sunspot number (Kulak *et al.* 2003b). The next stage of research on the ELF fields in the Earth-ionosphere cavity was the development of the Schumann resonance power spectrum decomposition method (Kulak *et al.* 2006). Thanks to this method, based on the idea of Fano resonance (Fano 1961), it is possible to decompose the power spectrum of the field in the cavity by separating the symmetrical part from other components of the spectrum. Because the symmetrical components of modal spectral maxima have a strict relationship with the resonant field component, the remaining components can be attributed to the waves propagating directly from the sources. The application of the decomposition method to study the spectra of inhomogeneous field equations showed that the frequencies of the maxima of resonant field component in the cavity (and their widths related to quality factor) are independent of the source-observer distance and are the only invariant parameters for all observers located in the cavity (Kulak *et al.* 2006). Thus, the use of the decomposition method for analyzing the observational power spectra of the Schumann resonances opened a new path for precise measurements of the Earth-ionosphere cavity parameters. The possibility of separating the resonance field component from the observed Schumann resonance spectrum also opened new possibilities in solving inverse problems and measurements of storm activity. Since the sum of the power of resonant modes is a measure of the current moment of instantaneous discharges in the cavity, it is possible to measure the global intensity of thunderstorms, without errors resulting from the addition of spectral components originating from direct waves.

The first application of the new method was a study of global storm intensity index, describing the daily activity patterns of three world storm centers (Nieckarz *et al.* 2009a). In another work it was shown that the selected time intervals of the storm intensity index closely correlates with the value of the field E_{0z} associated with the ionospheric potential (Nieckarz *et al.* 2009b). These results show that the decompositon method opens new opportunities for the quantification of contribution of thunderstorms to the global atmospheric electric circuit, in addition to the opportunities arising from the analysis of ELF radiation from lightning (Odzimek and Lester 2009). The application of the decomposition method has also contributed to a significant improvement in inverse solutions. The algorithm that was used to determine the distance consisted of searching for analytical spectra of the resonant field component most closely related to observational spectra, was based on an erroneous assumption that the observed Schumann resonance spectra describe the resonant field component. Thanks to the method of decomposition of observational spectra this inaccuracy can be avoided and the same categories of analytical and observational spectra can be compared.

The use of a single station, equipped with two orthogonal magnetic antennas, allows Schumann resonance to be recorded along any of great circles passing through the station (Kulak *et al.* 2014). For the first time using the spectral decomposition method, daily and seasonal studies of the location and intensity of the African storm center were carried out (Dyrda *et al.* 2014). This opened new possibilities for mapping global storm activity, especially when using multiple observation stations located on several continents. Another important application of the decomposition method is the continuous measurement of cavity parameters with a temporal distribution capacity of the order of minutes. This allows observing rapid changes in parameters caused by strong solar flares and tracking the *D*-layer disturbances caused by UV radiation, X rays and protons (Dyrda *et al.* 2015).

Current research focuses on more accurate modelling of the spherical Earth-ionosphere waveguide, taking into account the influence of solar terminator and ionospheric heterogeneities (Kudintseva et al. 2016, Nickolaenko et al. 2016). This enables improvement of inverse solutions for reconstructing the current moment of the sources observed using the global WERA system (Kułak and Młynarczyk 2011, Mlynarczyk et al. 2015, 2017a, b; Gołkowski et al. 2018). The global WERA system has played an important role in verifying the impact of ELF electromagnetic fields on the work of LIGO gravitational wave detectors (Coughlin et al. 2016).

After nearly 70 years since the first Schumann publications, the intensity of research related to ELF waves is not weakening and there is no indication that this will change in the near future. On the one hand, the Earth-ionosphere cavity turned out to be a large isotropic detector of the stream of particles penetrating the ionosphere, allowing to monitor the space weather. On the other hand, thanks to the long-range propagation of ELF waves, it enables global monitoring of strong atmospheric discharges of various types and storm centers, regardless of the position of the observer. Due to an advanced state of propagation modelling and inverse solutions, measurements of discharge parameters and storm center activity are carried out with high accuracy in absolute units. In the coming years, they will play an important role in tracking climate change on global scale (Williams *et al.* 2019). It should also be kept in mind that the research methodology developed for Earth can be easily used to the resonance cavities of planets and moons of the solar system (Kulak *et al*. 2013, Kozakiewicz *et al.* 2015). And that means further intensification of research.

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WSPÓŁCZESNE BADANIA REZONANSU SCHUMANNA

Streszczenie

Opublikowana przez W.O. Schumanna praca o wnęce Ziemia-jonosfera otwarła nowe kierunki badań (Schumann 1952a, b, c). Pierwszy związany jest z fizyką falowodów grunt-jonosfera i modelowaniem propagacji w zakresie ELF. Drugi koncentruje się na pomiarach wyładowań atmosferycznych, efektywnych w tym zakresie częstotliwości ze względu na dalekozasięgową propagację fal. Przeprowadzona przez M. Balsera i C.A. Wagnera pierwsza udana obserwacja naturalnego pola rezonansu Schumanna we wnęce (Balser i Wagner 1960) wywołała znaczne zainteresowanie. Pierwsze badania koncentrują się na analizie spektralnej i zmienności szumów atmosferycznych (Balser i Wagner 1962, Pierce 1963, Blackband 1964, Rycroft 1965, Polk 1969), oraz modelowaniu wnęki (Row 1962, Wait 1962, Jones 1964, Chapman i Jones 1964, Galejs 1965, 1970; Rycroft 1965, Madden i Thompson 1965, Jones 1967, Booker i Lefeuvre 1977, Tran i Polk 1979, Bliokh i in. 1980).

Falowód grunt-jonosfera modelowano początkowo przy pomocy pełnofalowej metody rozwiązań 3D. Nowy etap modelowania przyniosła praca Maddena i Thompsona (1965), w której autorzy postulują przyjęcie modelu TDTE (Two-Dimensional Telegraph Equations), w którym falowód zostaje zastąpiony dwuwymiarową sferyczną linią transmisyjną, w której równania polowe Maxwella zostają zastąpione równaniami telegrafistów dla napięć i prądów.

Pod koniec lat siedemdziesiątych C. i P. Greifingerowie (Greifinger and Greifinger 1978, 1979) dokonują kolejnego przełomu w modelowaniu falowodu grunt-jonosfera. Analizując mechanizmy wnikania składowej elektrycznej i magnetycznej pola fali do jonosfery, wprowadzają dwie różniące się od siebie wysokości charakterystyczne falowodu: wysokość elektryczną h_e i wysokość magnetyczną h_m. Wkrótce Kirillov (Kirillov 1993, Kirillov i in. 1997, Kirillov i Kopeykin 2002) zauważa, że wysokości charakterystyczne Greifingerów h_e i h_m są ściśle związane z parametrami jednostkowymi L i C dwuwymiarowej linii transmisyjnej, wprowadzonej przez Maddena i Thompsona (1965). Wysokości charakterystyczne stają się podstawowymi parametrami falowodu grunt-jonosfera pozwalającymi rozwiązywać w zakresie ELF zagadnienia propagacyjne i zjawiska rezonansowe we wnęce grunt-jonosfera (Kirillov i in. 1997, Mushtak i Williams 2002, Williams i in. 2006, Pechony i Price 2004, Kulak i Mlynarczyk 2013, Kulak i in. 2013, Galuk i in. 2015, Kudintseva i in. 2016).

Z biegiem lat badania obserwacyjne koncentrują się na pomiarach zmienności parametrów rezonansu Schumanna i poszukiwania ich przyczyn (Ogawa i in. 1968, Polk i Toomey 1972, Nickolaenko i Rabinowicz 1995, Nickolaenko 1997, Nickolaenko i in. 1998, Sátori 1996, Neska i Sátori 2006, Greenberg i Price 2007). Badane są zależności amplitud i częstotliwości poszczególnych modów rezonansu od czasu i przestrzennego rozkładu wyładowań atmosferycznych. Analizowany jest wpływ zaburzeń górnych warstw jonosfery na stan wnęki spowodowany gwałtownymi wzrostami aktywności słonecznej (Blackband 1964, Cannon i Rycroft 1982, Magunia 1996), oraz długoczasowe zmiany parametrów wnęki w przedziałach czasu obejmujących 11-letni cykl aktywności słonecznej (Kulak i in. 2003b, Sátori i in. 2005). Powstają prace modelowe uwzględniające wpływ różnych rodzajów zaburzeń na stan wnęki (Galejs 1972, Sentman 1983, Füllekrug 2000, Füllekrug i in. 2002, Williams i Sátori 2007, Sátori i in. 2016).

Williams (1992) wykazał, że amplituda 1 modu rezonansu Schumanna wzrasta wraz ze wzrostem średniej temperatury powietrza w tropikach, co otworzyło nowe możliwości pre-

cyzyjnego monitorowania klimatu (Rycroft i in. 2000, Williams i in. 2019). Już wcześniej w szeregu prac podejmowano próby odtwarzania globalnej aktywności burzowej na podstawie obserwacji widm rezonansu Schumanna. Wykorzystywano w tym celu uproszczone rozwiązania analityczne oparte na metodzie rozdzielenia zmiennych, opisujące składową rezonansową pola we wnęce (Galejs 1972, Clayton i Polk 1977, Polk i Toomey 1972, Heckman i in. 1998, Nickolaenko i Rabinowicz 1995, Nickolaenko i in. 1998, Shvets 2001, Yang i in. 2009). Analiza ścisłych rozwiązań niejednorodnych równań pola, uwzględniających czaso-przestrzenny mechanizm wypełniania wnęki przez punktowe źródło fal ujawniła, że istnieją znaczne odstępstwa realnego rozkładu pól we wnęce od uproszczonego, wynikającego z rozwiązań uzy-skiwanych metodą rozdzielenia zmiennych (Kulak i in. 2003a). Zastosowanie pełnych rozwiązań do rozwiązywania zagadnień odwrotnych otwarło nowy etap w badaniach rozmieszczenia źródeł i pomiarach parametrów wnęki (Kulak i in. 2003b).

Kolejnym etapem w badaniach pól we wnęce Ziemia-jonosfera było opracowanie metody dekompozycji widm mocy rezonansu Schumanna, opartej na idei rezonansu Fano (Fano 1961, Kulak i in. 2006). Zastosowanie metody dekompozycji do analizy obserwacyjnych widm mocy rezonansu Schumanna otwarło nową drogę do precyzyjnych pomiarów parametrów wnęki Ziemia-jonosfera. Pierwsze zastosowanie nowej metody dotyczyło badań przebiegu globalnego indeksu intensywności burzowej, opisującego dobowe przebiegi aktywności trzech światowych centrów burzowych (Nieckarz i in. 2009a). W innej pracy pokazano, że w wybranych przedziałach czasu indeks intensywności burz ściśle koreluje z wartością pola E_{0z} związanego z potencjałem jonosfery (Nieckarz i in. 2009b). Wyniki te pokazują, że metoda dekompozycji otwiera nowe możliwości dla szacowania roli aktywności burzowej w globalnym obwodzie elektrycznym atmosfery, oprócz innych możliwości w tym kierunku wynikających z analizy promieniowania ELF od wyładowań (Odzimek i Lester 2009).

Zastosowanie metody dekompozycji widm przyczyniło się do znacznej poprawy efektywności rozwiązań odwrotnych. Przy ich zastosowaniu przeprowadzono badania dobowe i sezonowe położenia oraz intensywności afrykańskiego centrum burzowego (Dyrda i in. 2014). Otwarły się nowe możliwości mapowania globalnej aktywności burzowej, szczególnie skuteczne przy zastosowaniu wielu stacji obserwacyjnych umieszczonych na kilku kontynentach. Innym zastosowaniem metody dekompozycji jest możliwość prowadzenia pomiarów parametrów wnęki Ziemia-jonosfera z czasową zdolnością rozdzielczą sięgającą pojedynczych minut. Umożliwiło to śledzenie gwałtownych zmian parametrów wywołanych silnymi rozbłyskami słonecznymi (Dyrda i in. 2015).

Obecne badania koncentrują się na dokładniejszym modelowaniu wysokości charakterystycznych sferycznego falowodu Ziemia-jonosfera, przy uwzględnieniu wpływu terminatorów i globalnych niejednorodności jonosfery (Kudintseva i in. 2016, Nickolaenko i in. 2016). Umożliwia to doskonalenie rozwiązań odwrotnych stosowanych do odtwarzania momentów prądowych źródeł obserwowanych przy pomocy globalnego systemu WERA (Kułak i Młynarczyk 2011, Mlynarczyk i in. 2015, 2017a, b; Gołkowski i in. 2018). Globalny system WERA odegrał ważną rolę w weryfikacji wpływu pól elektromagnetycznych ELF na pracę detektorów fal grawitacyjnych LIGO (Coughlin i in. 2016). Dzięki zaawansowanemu modelowaniu propagacji i doskonaleniu metod odwrotnych, pomiary parametrów wyładowań i aktywności centrów burzowych są prowadzone w jednostkach bezwzględnych z coraz większą dokładnością. W najbliższych latach odegrają one ważną rolę w śledzeniu zmian klimatu w skali globalnej (Williams i in. 2019).