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Ionospheric effects on terrestrial communications: Working Group 3 overview

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Telecommunications via ionospheric reflection of radio signals of ground-based transmitters are a traditional area. However, this technique is still in use in telecommunications, broadcasting, etc. Various problems have not yet been solved and some of them were studied in Working Group 3 (WG 3). Structure of WG 3 and the terms of reference of its four working packages are described in the introductory paper by Zolesi and Cander (2004). Here we describe the main results achieved in COST 271 in the following areas: i) large-scale fluctuations of planetary and gravity waves; ii) development of a new type of HF channel simulator; iii) geomagnetic storm effects on the *F*1-region ionosphere; iv) the sporadic *E*-layer and spread-*F* phenomena; v) the HF radio wave propagation over northerly paths; vi) how to increase the bit rate in ionospheric radio links. In general, substantial progress was achieved but some problems remain open for future investigations.

3.1. INTRODUCTION

In spite of the rapid development of GPS-type techniques, tropospheric microwave communications and other modern techniques, ionospheric radio propagation plays an important role in terrestrial communications, radio location, radar and remote sensing applications. Working Group (WG) 3 joined scientists dealing with such problems with emphasis on the European area, *i.e.* middle and high latitudes. The activity of WG 3 was defined by the following terms of reference:

Establishing the ionospheric effects (*i.e.* large-scale as well as small-scale ionospheric fluctuations and irregularity effects) on the behavior of the ionosphere and terrestrial communications, including remote sensing, radio location and radar techniques.

Investigations were organized into four Working Packages (WP):

WP 3.1 – Effects of large-scale ionospheric fluctuations on terrestrial communications, including remote sensing, radio localization and radar. WP 3.1 covered investigations of effects of gravity and planetary wave effects on the ionosphere and radio wave propagation, and part of high latitude, off great circle propagation studies.

WP 3.2 – Effects of small-scale ionospheric irregularities, interference and noise on terrestrial systems. WP 3.2 investigated effects of ionospheric irregularities on the HF channel by a theoretical approach with the objective to realize an HF channel simulator.

WP 3.3 – Mid-latitude ionospheric features in radio propagation models. WP 3.3 dealt with the impact of geomagnetic storms on the *F*1-region, with sporadic *E*-layers and examination of the spread-*F* phenomenon, all preferentially at European middle latitudes.

WP 3.4 – Development of methods and algorithms to minimize the deleterious effect of the ionosphere on terrestrial communications. WP 3.4 considered the problem of HF propagation over northerly paths. Also a method was proposed to counteract the deep fading that affects the skywave propagation so as to increase the bit rate.

More detailed information can be found in the five papers by Altadill, Zernov, Bencze, Warrington and Perrine, which describe in this issue the research and the results achieved in individual areas of WG 3.

Why did we deal just with the above problems? Planetary wave type effects on the ionosphere had been studied relatively little in the past, because planetary waves cannot penetrate directly into the ionosphere. However, such oscillations significantly affect the ionosphere and, thus, the radio wave propagation on time scales of days to weeks. As for gravity waves, effects of those of auroral origin have been broadly studied but much less activity was devoted in the past to gravity waves of different origin, namely meteorological origin and those related to solar terminator. They are important for ionospheric variability on time scales of tens of minutes to hours and, therefore, for forecasting. The ionosphere is substantially influenced by geomagnetic storms. While many authors studied storm effects on the *F*2-region, those on the *F*1-region have been studied very little (*e.g.*, Buonsanto, 1999). But, during geomagnetic storms, the *F*1-region plays a more important role in radio wave propagation, and under the *G*-conditions, when the weak *F*2-layer is screened by the *F*1-layer, the *F*1-region dominates the ionospheric radio wave propagation. The radio propagation is also remarkably affected by two types of ionospheric irregularities studied in WG 3, by sporadic *E*-layers and by the spread-*F* phenomenon. Wide deviations in the direction of arrival of ionospherically propagating radio signals from the great circle path, caused particularly at northerly paths by the presence of the ionospheric trough, can substantially deteriorate the quality of radio propagation and, therefore, have to be examined. The HF ionospheric channel simulators had been developed in the past as empirically based models (*e.g.*, Mastrangello *et al.*, 1999). Within WG 3 activities, a physically based software simulator has been developed for the HF ionospheric reflection fluctuating channel of radio propagation, which is qualitative progress in the field of HF channel simulators, necessary for HF radio link planning and good performance. HF ionospheric radio signal propagation needs much less infrastructure than satellite links and can achieve a very long distance transmission. Therefore methods to improve the quality of the HF ionospheric transmission of digital information are studied.

The investigations made in the framework of WG 3 resulted in the significant progress in some areas, as shown below.

3.2. EFFECTS OF GRAVITY AND PLANETARY WAVES

Gravity and planetary waves are responsible for a part of the uncertainty of ionospheric radio wave propagation predictions and forecasts for telecommunication purposes. If we succeed in predicting their effects on the ionosphere, it would be possible to noticeably improve the accuracy of predictions and forecasts. This is the motivation of COST 271 investigations into planetary and gravity wave effects on the ionosphere.

Gravity waves, oscillations with periods from several minutes to several hours, reach to the mid-latitude ionosphere either from the auroral zone in connection with geomagnetic and auroral activity, or from below where they are excited by various meteorological and other processes in the neutral atmosphere, or they are excited *in situ* by a solar terminator or solar eclipses. Their effects on the mid-latitude *F*-region ionosphere were studied in collaboration between the Institute of Atmospheric

Physics in Prague and Observatorio del Ebro in Roquetes (*e.g.*, Boška and Šauli, 2001; Šauli and Boška, 2001; Boška *et al.*, 2003).

The most important result of gravity wave studies for radio wave propagation is probably the regular occurrence of morning and evening wave bursts. They are regularly observed in the *F*-region ionosphere, particularly in the morning, when they occur so regularly that they should be included into short-term forecasts. These gravity waves are related to the solar terminator passage and related large and rapid changes in atmospheric temperature. The typical duration of wave events is about 4-6 h, their amplitudes in electron density or heights of levels of constant electron density show a high degree of variability, these gravity waves originate in the transition region between the *F*1- and *F*2-layers at heights of about 180-200 (220) km, and they propagate upwards and downwards simultaneously from that region. The gravity waves excited by the solar terminator remain in the spectra also during days of geomagnetic storms and display a similar vertical structure as during quiet days, while additional strong wave enhancements of auroral origin occur. The latter however do not exhibit vertical propagation. The sunrise terminator-related gravity waves are good candidates for inclusion in ionospheric predictions.

A similar vertical structure was observed with gravity waves excited by solar eclipses. The border of the eclipse shadow acts as a solar terminator. Eclipses are well predicted in advance, so their effects can be included in radio wave propagation forecast, but they occur very rarely, thus their practical importance is low.

Whereas ionospheric effects of gravity waves of auroral origin have been widely studied in the past, and the waves excited by solar terminator and solar eclipses have also been studied to some extent, the effects of waves of meteorological origin have been studied very little by others. The specific gravity wave events are those caused by meteorological cold front passages. The ionospheric response to such gravity waves is well pronounced and displays specific features, but it is less regular than that of the solar terminator. The dominant feature is remarkable strengthening of gravity wave activity in the period range of about 60-80 min. The lifetime of such events is up to 6 h, and their energy propagates upwards at an average rate of a few ms^{-1}.

Planetary waves are large-scale to global oscillations with periods of about 2-30 days, which are predominantly of tropospheric origin. When we deal with the planetary wave type oscillations in the ionosphere, it is better to use the term planetary wave signatures, because part of these oscillations is caused by *quasi*-periodic changes of geomagnetic activity, not only by planetary waves coming from below (Altadill and Apostolov, 2003). Planetary waves of tropospheric origin can penetrate to *F*-region heights only indirectly, for example through planetary wave modification of upward propagating tides in the Mesosphere and Lower Thermosphere (MLT) region. The planetary wave signatures in the *F*-region were studied in collaboration between Observatorio del Ebro in Roquetes, the Institute of Atmospheric Physics in Prague, and the Geophysical Institute in Sofia (*e.g.*, Altadill and Apostolov, 2001, 2003; Laštovička *et al.*, 2003).

The planetary wave signatures in the *F*-region occur as bursts of duration of several wave cycles. An important, albeit rather negative finding concerns the persistence of such events. The typical occurrence of planetary wave signatures with periods from 2 to 16 days is from 12 to 35% of the time respectively, and their typical duration ranges from 4 to 3 wave cycles respectively. However, the spectral distribution of duration of events is too broad to allow for a reasonable prediction of event duration based only on *F*-region measurements. This means that planetary wave signatures remain unpredictable from ionospheric measurements themselves, and we have to search for appropriate predictors both in the MLT region parameters and in geomagnetic activity.

The planetary wave signatures in the midlatitude *F*-region are limited both temporally, as shown above, and spatially, even though they are large-scale phenomena. Their typical longitudinal size was found to range from 80º for periods of 2-3 and 5-6 days to 180º for periods of 16 days.

As mentioned above, some planetary wave signatures in the *F*-region are of geomagnetic activity origin. It is of some importance (also for possible predictions) to know seasonal variations of the role of different causes of planetary wave signatures. Solar flux variations were found to be responsible for a very small contribution. The planetary wave signatures related to the geomagnetic activity tend to occur during summer half year. Those related to the planetary wave activity in the MLT region tend to occur during summer half of the year for planetary waves with shorter periods, and those with longer periods tend to occur during the winter half year.

3.3. THE HF IONOSPHERIC FLUCTUATING CHANNEL

To properly characterize the ionospheric reflection HF fluctuating channel of propagation on a physical basis, a comprehensive solution has been constructed for high frequency wave propagation in the 3D inhomogeneous (rigorously also anisotropic) ionosphere with local random inhomogeneities embedded. This entails a comprehensive solution to the problem of wave propagation in a random medium for the most general case of a 3D inhomogeneous dispersive medium with fluctuations of the parameters including the case of strong scintillation (strong fluctuation of the field amplitude), or that of the saturated regime of propagation. Although a rigorous solution to this problem is not currently available, the best available solution has been considered, based on the complex phase method (in classical terms, Rytov's method), which has been extended to the case of an inhomogeneous medium and a point source of the field.

First, Zernov (1980) extended this method to the case of a plane-layered background medium and a point source. This extension was intensively employed in a series of papers (Gherm and Zernov, 1995, 1998; Gherm *et al.*, 1997a,b, 2001a,b, 2002, 2003) to study effects due to fluctuations of the electron density in the plane-stratified ionosphere. Gherm and Zernov (1995) studied the statistical moments of the phase and log-amplitude of the HF field, in particular, the effect of Fresnel filtering. Subsequent papers (Gherm *et al.*, 1997a,b) were devoted to the effects on propagation of both narrow- and wideband pulses in the fluctuating ionosphere.

Finally, the most general theory was developed in the scope of the Project «Wideband HF and UHF simulators for ionosphericaly reflected and transionospheric channels», (under the financial support of the U.K. EPSRC Visiting Fellowships programme) where the effects of the anisotropy of the ionosphere (including the background ionosphere) were taken into account. This project was performed in collaboration between the University of St. Petersburg, St. Petersburg, Russia (NNZ and VEG) and the University of Leeds, Leeds, U.K. (HJS).

This investigation resulted in producing a physically based software simulator for the HF ionospheric reflection fluctuating channel of propagation, which overcame limitations of empirically based models. The wideband HF simulator constructed is based on a detailed physical model. It can generate an output giving a time realisation of the HF channel for any bandwidth (up to a MHz) and for any given time, path and conditions. To characterise the HF channel of propagation, an analytic-numerical technique has been used, which employs the complex phase method that was recently extended to the case of a 3D inhomogeneous and even anisotropic medium.

3.4. GEOMAGNETIC STORMS AND *F*1-REGION IONOSPHERE

The *F*1-region and its response to geomagnetic storm-induced disturbances have been studied much less than the *F*2-region, mainly because of its relatively small importance for radio wave propagation under undisturbed conditions. However, during geomagnetic storms under the *G*-conditions, when the *F*2-region electron density is so small that it is screened by the *F*1-region, the role of the *F*1-region is principal. These two above facts are the motivation of the *F*1-region studies in COST 271. These studies were done prevailingly in the Institute of Atmospheric Physics in Prague with small contributions from Spanish and Hungarian partners (*e.g.*, Burešová and Laštovička, 2001, 2003; Burešová *et al.*, 2002).

It was found that irrespective of the sign of the geomagnetic storm effect on *NmF*2 (maximum electron density in the *F*2-region), the effect on daytime electron density at the *F*1 heights at European higher middle latitudes was always negative (electron density depletion), if any at all. At European lower middle latitudes, the effects at *F*1-region heights were weaker and less regular. There is a significant seasonal variation of the geomagnetic storm effect on the *F*1-region with no significant effect of geomagnetic storms on electron density at the *F*1 heights in the range of 160-190 km during the summer half of the year except for the moderate-to-minor effect of the super storm. On the other hand, in the winter half of the year at higher middle latitudes there is a well-pronounced effect of magnitude increasing with height. A much larger effect is found in autumn and winter *versus* spring and summer for station Chilton in England. The pattern of the geomagnetic storm effects on the *F*1-region electron density does not appear to change with solar activity (solar cycle). The explanation of the observed effects is not sufficiently clear, but the upward motion of the boundary between the region dominated by molecular ions and the region dominated by atomic ions evidently plays a role.

Another interesting result is finding that for ionospheric storms with the positive phase, the maximum of storm effect is located well below the maximum of the *F*2-region.

3.5. SPORADIC *E*-LAYER AND SPREAD-*F* PHENOMENA

The radio wave propagation by reflection from well-developed sporadic *E*- (*Es*-) layers has been used in radio communication and radar location/ranging, and the spread-*F* phenomenon deteriorates the quality of radio signals propagating via the ionosphere. Therefore it was necessary to study these two phenomena and their occurrence. The studies were realized in the Geodetical and Geophysical Institute in Sopron (*e.g.*, Bencze and Bakki, 2002; Bencze and Märcz, 2002).

The ionosphere depends substantially on the 11-year solar cycle. However, it was found that there was no change in *h'Es* (height of the *Es*-layer) exceeding the accuracy of ionosonde scaling (5 km) between the solar activity maximum and minimum years (Bencze and Märcz, 2002). This means that the change in the average *Es*-layer height with solar cycle is not very important for radio wave propagation predictions.

Bencze and Bakki (2002) analysed measurements from Uppsala (59.8°N) and Lannion (48.45°N). The daily variation of the simultaneous occurrence of spread-*F* and geomagnetic AE index enhancements displayed night time maximum. The number the simultaneous occurrence attains at the time of the morning is a maximum 30% of the total number of spread-*F* occurrences in Uppsala and 23% in Lannion. A delay of about 4 h was observed between the morning maximum of the simultaneous occurrence of spread-*F* and AE enhancements at the mid-latitude Lannion station as compared with Uppsala station. This delay may be connected with the propagation of travelling ionospheric disturbances from auroral latitudes.

Based on the results that concern travelling ionospheric disturbances as a source of ionospheric irregularities in the *F*-region, the second source, instabilities, may contribute during the morning maximum by about 70% to the development of irregularities. Thus, instabilities appear to be the dominant source of irregularities and spread-*F*. However, it seems that the role of travelling ionospheric disturbances may not be neglected.

3.6. HF RADIO WAVE PROPAGATION OVER NORTHERLY PATHS

Wide deviations in the direction of arrival of ionospherically propagating radio signals from the Great Circle Path (GCP) have serious implications for the planning and operation of communications and radiolocation systems operating within the HF-band. Perhaps the most obvious example lies in the operation of radiolocation systems which usually operate by measuring the direction of arrival at several receiving sites. The location of the transmitter is then estimated from the intersection of the individual lines of bearing from each receiving site, and deviations from the GCP will therefore adversely affect the estimate of the transmitter location. The importance of off-great circle propagation extends beyond radiolocation to almost any HF system which employs directional antennas. With these systems, there is a significant possibility that performance will be degraded at times when the supported propagation path is in directions well displaced from the main lobe of one or both of the transmitting or receiving antennas.

In addition to the large scale tilts which cause gross deviations of the signal from the great circle direction, irregularities in the electron density distribution cause signals associated with each propagation mode to arrive at the receiver over a range of angles in both azimuth and elevation. Such directional spread of the received signal energy is an important parameter to be considered in the design of multi-element receiving arrays and the associated signal processing methods used, for example, in radiolocation or adaptive reception systems. It is often assumed in the design of such systems that the signal environment comprises a limited number of specularly reflected signals arriving at the antenna array from well-defined directions. However, for northerly paths, this is often not the case, and azimuthal standard deviations of several tens of degrees have been measured over polar cap paths (Warrington, 1998).

A common feature of northerly HF propagation is the large Doppler and delay spreads imposed on the signal. The magnitude of these effects is such as to severely limit the data throughput achievable in HF communications systems due to current technological limitations in modem design (Angling *et al.*, 1998). The large Doppler spreads are often associated with directional spreading and recent work (Warrington *et al.*, 2000) has indicated that adaptive beam/null steering from an array of antennas can be employed to exploit the directional spreading effects to reduce the apparent Doppler spread at the modem input.

Various measurements of off great-circle propagation effects over a range of northerly paths and their interpretation have been undertaken over a number of years. Significant progress has been made over the COST 271 period. This work was done by a team of the University of Leicester. The important results of this research, to consider work in progress aimed at further improving our understanding of the high latitude propagation mechanisms, and to report on methods being developed for taking these propagation effects into account when designing and operating HF radio systems.

3.7. A WAY TO INCREASE THE BIT RATE IN IONOSPHERIC RADIO LINKS

HF waves (3-30 MHz), when propagated through the ionosphere, can achieve very long distance transmissions with a minimal infrastructure compared to satellite links, for example. This multipath and multimode channel strongly degrades transmissions (mainly fading and frequency selectivity). For this reason, the data rate of standard scalar HF modems does not exceed 4.8 kbps in 3 kHz bandwidth.

The originality of this study is to use a heterogeneous array to improve the HF transmission. Indeed, it has been shown that such a device could achieve the direction finding regarding the incoming polarization as a decorrelation factor and, consequently, that the diversity of the spatial responses could, to some extent, replace the space diversity (Erhel *et al.*, 1998, 2004).

The array processing performs on a set of four active collocated antennas or a circular array and the corresponding coherent receiving channels. The spatio-temporal equalization resorts to LMS (Least Mean Square) algorithm as the synchronization is based on a «Zero Crossing Detector».

It has been shown that a heterogeneous array can greatly improve the HF transmission, now offering the possibility to transmit images through the ionospheric channel. The general principle of the transmission system is described in the paper and experimental results are provided to show that this technique can increase the data rate, reaching 15 kHz within a 3 kHz bandwidth (QAM-64) without coding or interleaving. That work was realized at Université de Rennes1 and Centre de Recherches des Ecoles de Coëtquidan.

3.8. CONCLUSIONS

Tasks of the four working packages of WG 3 have been defined by the four terms of reference presented in the introductory paper by Zolesi and Cander (2004). As for WP 3.1, much more was done than required by the terms of reference. The percentage contribution of investigated oscillations to the variability of *foF*2 has been established, plus the percentage of time when these oscillations occur and persistence of wave events have been estimated, main sources of wave oscillations have been identified including their relative role, and information on predictability for ionospheric predictions has been obtained. The task of WP 3.2 was modified. Some information about the effects of irregularities was obtained, but the most important scientific result and practical product, the new physically based HF channel simulator, was constructed out of the original terms of reference. On the other hand, work done in WPs 3.3 and 3.4 essentially corresponds to the terms of reference. Significant progress was achieved in knowledge of the effects of large-scale irregularities on the ionosphere, particularly geomagnetic storm effects on the *F*1-region. Considerable progress has also been reached in understanding the HF radio wave propagation along northerly paths, strongly affected by the ionospheric trough. Major progress has been achieved in the ionospheric HF transmission of digital information based on the utilization of a heterogeneous array. This progress now allows us to transmit via the ionosphere pictures over distances of several hundred kilometers without loss of quality.

In spite of the considerable progress achieved, various open questions must be addressed in future investigations. For instance, the planetary and gravity wave effects on the ionosphere and radio propagation require better quantification and further research into possible predictions, and the investigations need to be broadened by effects of ionospheric infrasonic waves and by studies of possible impacts on GNSS-based techniques. Further improvement of knowledge on digital radio systems would be very valuable, particularly as concerns predictions and methods of reliability estimating. The extension of HF simulators to the MF band is needed. Increased capacity of the HF radio links should be a valuable output of future investigations. The space weather impact on the ionosphere and radio propagation and its prediction based on new space weather research products is another challenging area of investigations.

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