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4

Space plasma effects on Earth-space and satellite-to-satellite communications: Working Group 4 overview

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This paper summarizes the the activities carried out by Working Group 4 of COST 271 Action. The structure of this Working Group included four Working packages that were dealing with different aspects of the same overall problem related to space plasma variability and irregularities effects on advanced satellite systems. General comments about the most relevant achievements and possible future lines of research are given.

4.1. Introduction

At present to assess the effect of space plasma variability and irregularities on satellite systems is becoming an important part of planning of advanced applications of such systems. This aim was chosen as the key objective of Working Group 4 of the COST 271 Action. The structure of this Working Group included four Working Packages dealing with different aspects of the same overall problem covering ionospheric scintillations observations and modelling, development of algorithms for the forecasting and nowcasting of Total Electron Content (TEC), study of ionospheric disturbances generated by natural and anthropogenic processes, and the effects of electron density and TEC gradients on Earth-space and satellite-to-satellite communications. The details of these investigations and the results achieved can be found in the respective papers that correspond to each of the Working Packages of WG 4. General comments about the major achievements and possible future lines of research dealing with the same topics are given below.

4.2. Effects of space plasma variability and irregularities on Earth-space and satellite-to-satellite communication channels

The propagation of satellite signals through ionospheric irregularities generates modifications of the signals like intensity and phase fluctuations and rapid variations of angle of arrival. These phenomena are known as ionospheric scintillations and are observed particularly at low and high latitudes.

The GISM model has been further developed (Beniguel, 2002). It uses the Multiple Phase Screen technique and gives statistical characteristics of transmitted signals, fade duration and other parameters like signal loss of lock probability. Maps of scintillation index $S4$ and phase standard deviations can be produced.

A new hybrid propagation model to describe ionospheric scintillations has been developed that includes generating a 2D random screen by means of the complex phase method (Gherm *et al.*, 2002). This can result in a full shaped model able to extract not only scintillation indices, but also additional spectral information and model time series particularly suited for system-oriented problems.

Both GISM and the new model use as background ionosphere the 3D and time dependent NeQuick model of electron density that is one of the ionospheric models developed in the framework of the previous COST 251 Action (Radicella and Leitinger, 2001).

At present, it is widely accepted that at high latitudes phase scintillation activity is high and dominant while intensity scintillation is low and negligible. This scenario is based on several scintillation experiments done by means of GPS scintillation monitors.

Forte and Radicella (2002) have shown that data detrending, when the separation of deterministic and stochastic components is done using a fixed cut-off frequency, can lead to a misleading data interpretation. An experiment for measuring these effects on ionospheric scintillation information pointed out from GPS signals has been set up at auroral latitudes being run at the Sodankyla Geophysical Observatory (University of Oulu). A GPS receiver with a sufficiently high sampling rate has been used to measure the carrier phase and signal-to-noise ratios at $L1$. The preliminary result of the experiment seems to confirm the theoretical mechanism suggested as an explanation for the occurrence at high latitudes of high phase scintillation against low intensity scintillation. With these results new ways of describing scintillation effects at system level can be determined.

An effort was also made by Forte *et al.* (2002) to interpret experimental scintillations intensity data in a way useful to determine the impact of these phenomena on satellite navigation systems. Attention has also been given to the comparison between experimental data and models predictions. It can be stressed that the models fail to describe the patchy structure of irregularities, a typical feature of ionospheric irregularities.

4.3. Development of algorithms and software to treat disturbances in Earth-space and satellite-to-satellite communications

Unpredictable variability of the ionospheric parameters due to disturbances related to the ionosphere-magnetosphere system limits the efficiency of communications affected by the ionosphere by causing serious technological problems including range errors, scintillations of satellite signals and others propagation problems. It is known that in such cases mathematical modeling of the variability based on first physical principles is extremely difficult. Therefore data driven models such as Neural Networks based models can be used to forecast ionospheric parameters like TEC. The only requirement for the success of data driven models is the availability of reliable data, which can represent the characteristics of the process to be modeled.

The Middle East Technical University Neural Networks (METU-NN) technique to forecast 10 min values of the vertical Total Electron Content (TEC) values up to 24 h ahead during high solar activity in the current solar cycle has been applied to TEC data evaluated from GPS measurements from 2000 to 2001 at Chilbolton (51.8 N, 1.26 W). An additional validation has been performed using an independent data set. The construction work of the Neural Network based model is carried out in the development mode. It is composed of «training phase or learning phase» and «test phase» (Tulunay *et al.*, 2004a,b). The good results of this investigation indicate the potential of the Neural Networks techniques to forecast local vertical TEC values. The possible extension of the same technique to forecast two dimensional TEC maps could provide a very useful tool to forecast the effects of the ionosphere on satellite navigation.

Since 1995, DLR/IKN has been operating a new system for regularly processing data and producing TEC maps over the European region based on GPS measurements by the International GPS Service (IGS). The existing large database, containing data from all solar/geomagnetic conditions, is a very useful tool for the validation of all types of ionospheric effects calculations particularly for highly disturbed ionospheric conditions where the use of other measurement techniques (*e.g.,* ionosondes) is limited. Furthermore, DLR/IKN has developed the software modules for deriving ionospheric grid errors in the EGNOS System Testbed (ESTB) in real-time.

Auto- and cross-correlation procedures have recently been developed for predicting both the critical frequency of the *F*2-region and the TEC, strongly relating the short-term forecast to present and future geomagnetic activity. Preliminary results of these methods/procedures have already been tested and reported for the one-dimensional case when forecasting is performed at a given location based on GPS-TEC measurements, solar and geomagnetic activity indices. Extending such a prediction to several locations in a given region, instantaneous maps of the forecast can be constructed covering the region of interest.

Other investigations on TEC and critical frequency of *F*2 variability have been carried out together with the application of clustering techniques to characterize *F*2 critical frequency behavior.

4.4. Application of theoretical considerations to the study of space plasma effects

A series of investigations have been carried out to study different aspects of the plasma characteristics in the magnetosphere-ionosphere-thermosphere system. Electromagnetic emissions at an ample range of frequencies measured on-board of low orbiting satellites have shown that during strong geomagnetic storms a series of phenomena are observed in same regions of the satellite orbital environment (Błecki *et al.,* 2003). A study was done on the impact of magnetospheric disturbances on the daily critical frequency of *F*2 and considerations on the use of both topside and ground vertical soundings to this purpose have been made (Rothkaehl *et al.*, 2003). Also HF electromagnetic noise in the ionosphere has been investigated using data from the Coronas-I satellite. The results show that the electromagnetic noise introduced by broadcast stations can disturb the ionospheric environment particularly at night (Rothkaehl and Klos, 2002).

The possible connection between earthquakes and disturbances in electromagnetic emissions has been studied.

Also the interaction between the body of the satellite and the surrounding ionospheric plasma has been investigated. It has been shown that the enhancement of radiation between the local plasma frequency an the *F*2 critical frequency can be correlated to interaction between the oscillation of electrostatically trapped particles in the wake of a spacecraft and superthermal electrons.

4.5. Effects of the vertical and horizontal gradients of electron density on Earth-space and satellite-to-satellite communication

The ionosphere introduces a group delay in satellite signal and is at present the main source of error for satellite navigation systems that operate at single frequency. The possible dependence of these errors on different parameters has been described in the research done by Nava (2000) with a systematic approach. NeQuick model has been used to assess this dependence and tests with experimental data have been performed. The results obtained suggest a way to «build-up» a correcting error function that applied to vertical TEC could «bind» the error on slant TEC after «back conversion». Appropriate model simulations could indicate the influence of thin shell curvature, latitudinal and longitudinal gradients on conversion error as a function of location and satellite elevation and azimuth.

Some ionospheric features observed during geomagnetic disturbed periods, were investigated using particular sets of GPS derived slant total electron content measurements: «Supertruth» data. These data are high quality slant total electron content measurements obtained at 5 s sampling rate, using 25 ground stations located in the U.S.A., during specific time periods. The coinciding pierce point technique used has shown that a strong correlation between *Dst* index variation and mapping function errors magnitude exists. Since mapping function errors reflect the presence of strong electron density and TEC gradients, the coinciding pierce point technique indicated that in some cases it is possible to detect some ionospheric storm effects in near-real-time (Nava and Radicella, 2003).

Information about the topside electron concentration distribution is not obtainable from ground-based measurements. In past decades only few satellites were equipped with ionosondes to sound the ionosphere above the *F*2 maximum (topside sounders). Ionospheric electron density models have their topside formulation based on old databases or different kinds of measurements. NeQuick and IRI models have been used for comparisons with topside sounder profiles (Coïsson, 2002). From the study it appears that the NeQuick model performance is strongly affected by its topside thickness parameter, indicating the need for an improvement of its formulation. The study also shows that the topside formulation of IRI leads to an overestimation of the electron density in the upper part of the profiles, and consequently an overestimation of TEC.

With the increasing use of radio systems for practical applications, particularly satellite-based navigation and positioning, interest is now turning to propagation effects on satellite-to-satellite paths. One specific aspect driving such investigations is concern over future requirements for the station-keeping of satellites in the commercially very important, but potentially congested, geostationary orbit. Geostationary satellites are currently tracked using a network of ground stations. A future possible development could involve positioning making the use of a satellite navigation system, like GPS. However, since the GPS system was designed primarily for terrestrial users the satellites have nadir-directed antennas. In consequence, reception in geostationary orbit would involve the use of signals transmitted by GPS satellites on the far side of the Earth. The model simulation study for GPS-to-geostationary satellite ray paths has shown that very large TEC values may be encountered (Bailey and Kersley, 2003, in Radicella *et al.*, 2004). It must be noted that for some extreme situations where the trajectory traverses the equatorial ionosphere at grazing incidence the TEC estimates could give rise to positioning errors in excess of 0.5 km. It is clear from the study that in any use of GPS signals for the station-keeping of geostationary satellites it would be necessary to exclude any dependence on signals where the ray-path geometry is close to eclipse, particularly close to the equatorial plane.

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