2

Assessment of space plasma effects for satellite applications: Working Group 2 overview

REINHART LEITINGER ([1]) and NORBERT JAKOWSKI ([2])

([1]) *Institute of Physics, Institute for Geophysics, Astrophysics and Meteorology (IGAM), University of Graz, Austria*
([2]) *Deutsches Zentrum für Luft und Raumfahrt (DLR), Institut für Kommunikation und Navigation (IKN), Neustrelitz, Germany*

An important part of the tasks of Working Group 2 of the COST Action 271 «Assessment of space plasma effect for satellites applications» is the assessment of novel data sources for information about the state of ionisation of the ionosphere. This report deals with those aspects which are not represented adequately in the scientific papers in this issue. Here emphasis is given to the product aspect (data and model collections, descriptions of methods and algorithms, availability of products, expected future developments) and the links between the past COST Actions 238 and 251 with the present Action 271 and with possible future cooperations. Working Group 2 was leading in the transionospheric propagation aspects of possible products for the International Telecommunication Union's Radiocommunication (ITU-R) Study Group 3. This report gives a short overview emphasizing future developments.

2.1. Introduction

From the beginning, space plasma research (essentially meaning ionosphere and plasmasphere research) had both scientific and applicational aspects. The scientific aspects are multi-disciplinary (from geophysics and plasma physics to wave propagation research) and the application aspects have multiplied with the availability of artificial satellites transmitting radio signals. The transionospheric propagation of radio waves (satellite to ground and satellite-to-satellite) is increasingly important, has a huge user community, and an enormous economic value. All application systems are influenced by plasma propagation effects. Recently the applicational interests have moved from Communication Satellites to Global Navigation Satellite Systems (GNSS) with satellites having orbital periods of 12 sidereal hours and transmitting *L*-band signals. Their radio signals are not only used for satellite based navigation but also for positioning with various users from advanced geodesy to surveying. Transionospheric propagation expertise is needed to assess system capabilities and limitations, to advise on propagation errors and to calculate corrections.

On the other hand, GNSS signals provide ionospheric information on a global basis. We are moving quickly from the «electron content» point of view to the remote sounding point of view. The latter needs careful assessment, validation and verification of inversion and imaging methods and finally the development of data assimilation systems.

We have some hope that we will continue to have Low Earth Orbit (LEO) satellites with VHF/UHF beacons (frequencies around 150 and 400 MHz) which provide the data for high resolution ionosphere tomography.

The novel data sources will not (and should not) replace the classical ones. The main problem with GNSS is the coupling of spatial with temporal changes. We continue to need an adequately dense network of ionosondes which provide independent information at well defined locations.

2.2. The main tasks of Working Group 2

Working Group 2 has three Work Packages:

– Plasma effects on GNSS applications.

– Assessment of plasma propagation errors in navigation systems and merits and shortcomings of novel data sources.

– Investigation of extremes of ionization.

The papers of Working Group 2 (Jakowski *et al.*, 2004c,d; Kersley *et al.*, 2004; Leitinger *et al.*, 2004) report on most of the important aspects of Work Packages 1 and 3.

Work Package 2 is divided into several assessment tasks. A part can be considered to be finished and the most important results are found in the WG 2 papers, another part will finish by the end of the Action, the foundation for the remainder is laid, but work will have to be finished outside COST Action 271.

These are:

– To assess ionospheric effects in non-ionospheric applications of GNSS signals

a) Ionospheric influences in the use of GNSS occultation for stratosphere / troposphere applications.

b) The effect of higher order ionospheric propagation errors in advanced ground based applications, like water vapour retrieval.

– To assess GNSS related systems to gain ionization data by

a) 3D and 4D imaging of the ionosphere;

b) adaptive modeling;

c) data ingestion into ionospheric models / data assimilation systems.

Detailed reports are available through the Working Group 2 web site: http://www.uni-graz.at/igamwww/cost271/.

Two groups of tools have been developed for and within Working Group 2:

– models for assessment studies;

– data collections.

These tools have been tested by participants in the COST 271 Action and are now available for the ionospheric research community (and strictly for non commercial applications only). Relevant information is available through the Working Group 2 Web site.

One effort within Work Package 3 is the collection of «extremes and peculiar cases», meaning unusually high or low electron content values, gradients, fluctuations from:

– magnetic storm effects;

– Travelling Ionospheric Disturbances (TIDs);

– peculiar (and partially unexplained) effects not related to storms or TIDs.

This collection too is available through the Working Group 2 Web site.

2.3. Models and other tools for assessment studies

The foundation for all assessment studies are suitable electron density models. A strong effort was made to bind over monthly median modelling efforts and results from Actions 238 and 251 to this COST Action and to apply modifications and improvements to gain realistic models for actual conditions.

Two important developments were made which should be seen in the context of «profiler» type electron density models. These use «anchor points» for the height profile of electron density, in most cases the peaks of the *E*-, *F*1- and *F*2-layers. Sub-models («maps») are used for peak heights and peak densities. The models developed under the auspices of the COST Actions 238 and 271 (a modification of the Di Giovanni-Radicella (DGR)-model for COST 238 (COSTprof for COST 271) are profiler models. «The model family» developed at Trieste and Graz (NeQuick, COSTprof, NeUoG-plas) and the International Reference Ionosphere are profilers.

The two modifications are:

– Replace monthly median maps by «data grids» for the *F*2-layer peak (Leitinger *et al.*, 2002a).

– Add smaller scale static and dynamic 3D structures by means of «model modulations» (*e.g.*, Leitinger and Rieger, 2004).

The «data grids» are files with *F*2 peak electron density and peak height (and other values) over equidistant grids in geographic coordinates. Grid spacing is 2.5° in latitude and 5° in longitude. In general, it is sufficient to produce one set of data grids per hour and to use Fourier interpolation to densify temporal spacing (*e.g.*, to one data grid per quarter hour or per 10 min). The data grids are used with spline interpolation in universal time and with third order polynomial interpolation in latitude and longitude (Leitinger and Radicella, 2002).

«Model modulation» means multiplication of the large scale background model with three dimensional and time dependent models for ionospheric structures like the main trough of the *F*-layer (Feichter and Leitinger, 2002a,b), large scale TIDs, various other troughs and ridges. The «modulations» provide values larger zero only, a value of one meaning «background model not changed».

The general assessment model construction scheme is now as follows:

1) Select the background «profiler» model.
2) Prepare the data grids.
3) Decide on the modulations to be used (*e.g.*, on TID properties).

The specialised assessment model is used to calculate satellite to ground or satellite to satellite electron content («forward modelling») to which the evaluation method in question is applied. The evaluation results are compared «with the truth», namely electron contents or electron densities calculated from the specialised assessment model. Example: an assessment study is based on «uncalibrated» satellite to ground slant electron contents, the evaluation method produces vertical electron contents for the location of receiving stations which are compared with vertical electron contents calculated from the assessment model.

«Open to everyone» data allow the comparison of different evaluation methods. «Blind» assessments are also possible: the research group that wants to test an evaluation algorithm defines the wanted link geometries (satellite to ground and/or satellite to satellite links), time structure and satellite orbits and gets artificial «observations». The type of model used is not revealed and the comparison between «model truth» and «evaluation results» is done by the producers of the assessment data.

2.4. Overview on assessment studies carried out

Since the German satellite CHAMP happened to be operational during most of the lifetime of the COST Action 271 it was considered very important to give relevant assessment studies the highest priority (*cf.* Jakowski *et al.*, 2004a,c,d). The following list is not complete but gives a good impression on CHAMP related activities:

– Validation of CHAMP Ionospheric Radio Occultation (IRO) results in general (Jakowski *et al.,* 2002, 2004b).

– Comparison of ionospheric electron density profiles from CHAMP with the NeQuick model (Cueto *et al.*, 2003) and the IRI model (Jakowski and Tsybulya, 2003).

– Comparison of radio occultation and ionosphere tomography (Spalla *et al.*, 2002; Malan and Jakowski, 2003).

The foundations for the assessment of other novel data sources, especially the inter-comparison of different methods to retrieve vertical electron content from GPS observations, are now complete (see Section 2.3), the assessment and inter-comparison studies themselves will be continued in follow-up studies.

Another group of assessment studies was done for space based navigation (Jakowski *et al.*, 2004c,d).

Other assessment, validation and verification tasks among others comprise space based radars (Cannon and Chan, 2003).

2.5. The HIRAC campaign and regional data collections

The High Rate Measuring Campaign (HIRAC/SolarMax) was an enterprise of the International GPS Service (IGS) with the aim to extract ionospheric data with sampling rates between one and three seconds from GPS and GLONASS signals (Feltens *et al.*, 2001). The campaign was carried out from 23 through 29 April, 2001. Around 100 receiving stations participated and delivered data into a dedicated archive. The data are very well suited to investigate smaller scale structures, especially dynamic ones as TIDs, on a nearly global basis. HIRAC was primarily aimed at high latitudes and at the crest regions of the equatorial anomaly, but because of the distribution of IGS and other GPS receiving stations data coverage in Northern mid latitudes was considerably better than in other regions. For COST 271 participation see, *e.g.*, Šauli *et al.* (2003) and Stolle *et al.* (2003). HIRAC related data with special interest for COST 271 are found in the TECEDA data archive (see below).

In many countries dense networks of dual frequency GPS receivers exist which could provide an excellent database for dedicated studies of smaller scale phenomena, *e.g.*, of Traveling Ionospheric Disturbances (TIDs). In connection with COST 271 the exploitation of such a network was tested at Graz (Rieger, 2002; Rieger and Leitinger, 2002).

2.6. Data banks, data collections, products of COST Actions 238 and 251

There are two European electron content data sets for longterm studies, namely the data derived by means of the Faraday effect on the VHF signals of geostationary satellites received at Firenze, Graz and Neustrelitz («Faraday-TEC») and data derived by means of the Differential Doppler effect on the 150/400 MHz signals of the (former) Navy Navigation Satellites (NNSS-TEC) received at Graz/Austria and Katlenburg-Lindau/Germany. The contact for Faraday-TEC is Paolo Spalla (P.Spalla@ifac.cnr.it), for NNSS-TEC Reinhart Leitinger (reinhart.leitinger@uni-graz.at).

The contact for the GPS-based regional maps produced at Neustrelitz is Norbert Jakowski (Norbert.Jakowski@dlr.de; see also the Internet address http://www.kn.nz.dlr.de). For the TECEDA data bank and other data products of interest for studies related to Working Group 2 of COST 271 see Stamper *et al.* (2004).

Electron content related products of COST 238 (PRIME) and COST 251 are found in the Working Group 2 Web page http://www.uni-graz.at/igamwww/cost271/. This is also the place for the electron density assessment models and relevant data and for the collection of extremes of ionization and of peculiar cases (see above). The Working Group 2 Web site will survive the end of COST Action 271 at least until relevant decisions are made in the frame of succeeding European projects. For access conditions outside the COST 271 Action contact Reinhart Leitinger (reinhart.leitinger@uni-graz.at).

2.7. PRODUCTS FOR ITU-R

So far one product was generated under the auspices of COST Action 271 and delivered to ITU-R, namely the monthly median electron density model NeQuick(ITU-R) (Leitinger *et al.*, 2002b). Another product is the scintillation model GISM. COST 271 has declared an interest in the model but is not directly involved in it.

For transionospheric propagation of radio waves Working Group 2 is able to suggest answers or partial answers to several open «Questions» of ITU-R Study Group 3 and to provide material to improve ITU-R Study Group 3 «Recommendations». Material produced are cumulative statistics of solar activity, geomagnetic disturbances and ionospheric conditions.

Working Group 2 has gained a lot of experience with the ITU-R (formerly CCIR) maps, mainly in connection with its electron density models. This experience is used to give advice for future ITU-R mapping efforts.

Working Group 2 has its own mapping efforts and has produced *F*2-layer peak density and peak height maps which are offered to ITU-R. For transionospheric propagation purposes these new maps are much better suited than the original *foF*2 and *M*(3000)*F*2 maps which are tuned to HF (terrestrial) propagation. With the ITU-R (CCIR) products it is necessary to combine three maps to produce *F*2-layer peak height which is a process leading to artificial smaller scale structures in peak height: this is avoided in the COST 271 maps.

2.8. OPEN QUESTIONS AND FUTURE ASPECTS

Not all tasks defined originally could be finished. This is especially true for the assessment studies to assess GNSS related systems to gain ionization data by data ingestion into ionospheric models/data assimilation systems.

The main reason for the delay is that data ingestion into ionospheric models (one development step from «adaptive modeling») is emerging only now. Full data assimilation systems (meaning operational systems which use data from different sources to guide theoretical or hybrid models in near-real-time) do not exist yet. Research work is done by several groups but it seems that this work will need considerably more time. Relevant assessment studies will be one of the important topics of follow-on projects.

REFERENCES

CANNON, P.S. and A.H.Y. CHAN (2003): Some ionospheric effects on space based radars, in *Proceedings of the 3rd COST 271 Workshop*, 23-27 September 2003, Spetses, Greece.

CUETO, M., N. JAKOWSKI, K. TSYBULYA, S.M. RADICELLA and M.HERRAIZ (2003): Comparison of ionospheric electron density profiles from CHAMP satellite with NeQuick model, in *Proceedings of the 3rd COST 271 Workshop*, 23-27 September 2003, Spetses, Greece.

FEICHTER, E. and R. LEITINGER (2002a): Properties of the main trough of the *F*-region derived from Dynamic Explorer 2 data, *Ann. Geophysics*, **45** (1), 117-124.

FEICHTER, E. and R. LEITINGER (2002b): The trough model, *Acta Geod. Geophys. Hung.*, **37**.

FELTENS, J., N. JAKOWSKI and C. NOLL (2001): High-Rate SolarMax IGS/GPS Campaign «HIRAC/SolarMax», *CDDIS Bulletin*, **16** (3), 2001.

JAKOWSKI, N. and K. TSYBULYA (2003): Comparison of ionospheric radio occultation CHAMP data with IRI-2001, *IRI Newsl.*, **10** (1,2,4-7).

JAKOWSKI, N., A. WEHRENPFENNIG, S. HEISE, CH. REIGBER, H. LÜHR, L. GRUNWALDT and T. MEEHAN (2002): GPS Radio Occultation Measurements of the Ionosphere from CHAMP: early results, *Geophys. Res. Lett.*, **29** (10), 10.1029/2001GL014364.

JAKOWSKI, N., K. TSYBULYA, S.M. STANKOV and A. WEHRENPFENNIG (2004a): About the potential of GPS radio occultation measurements for exploring the ionosphere, in *Proceedings of the Second CHAMP Science Meeting*, 1-4 September 2003, GFZ Potsdam (accepted).

JAKOWSKI, N., K. TSYBULYA, J. MIELICH, A. BELEHAKI, D. ALTADILL, J.C. JODOGNE and B. ZOLESI (2004b): Validation of GPS radio occultation measurements on CHAMP by vertical sounding observations in Europe, in *Proceedings of the Second CHAMP Science Meeting*, 1-4 September 2003, GFZ Potsdam (accepted).

JAKOWSKI, N., R. LEITINGER and M. ANGLING (2004c): Radio occultation techniques for probing the ionosphere, *Ann. Geophysics*, **47** (suppl. to no. 2/3), 1049-1066 (this volume).

JAKOWSKI, N., R. LEITINGER and L. CIRAOLO (2004d): Behaviour of large scale structures of the electron content as a key parameter for range errors in GNSS applications, *Ann. Geophysics*, **47** (suppl. to no. 2/3), 1031-1047 (this volume).

KERSLEY, L., D. MALAN, S.E. PRYSE and LJ.R. CANDER (2003): Further investigations on the verification of TEC measurements by different techniques, in *Proceedings of the 3rd COST 271 Workshop*, 23-27 September 2003, Spetses, Greece.

KERSLEY, L., D. MALAN, S.E. PRYSE, LJ.R. CANDER, R.A. BAMFORD, A. BELEHAKI, R. LEITINGER, S.M. RADICELLA, C.N. MITCHELL and P.S.J. SPENCER (2004): Total electron content – A key parameter in propagation: measurement and use in ionospheric imaging, *Ann. Geophysics*, **47** (suppl. to no. 2/3), 1067-1091 (this volume).

LEITINGER, R. and S.M. RADICELLA (2002): Electron density models for assessment studies - A progress report, in *Proceedings of the 2nd COST 271 Workshop*, 2-4 October 2002, Faro, Portugal.

LEITINGER, R. and M. RIEGER (2004): The TID model for modulation of large scale electron density models, *Ann. Geophysics* (accepted).

LEITINGER, R., S.M. RADICELLA, E. FEICHTER and B. NAVA (2001): Electron density models suitable for assessment studies which involve satellite to ground and satellite to satellite electron content, in *Proceedings of the International Beacon Satellite Symposium*, Boston, U.S.A., edited by P. DOHERTY.

LEITINGER, R., S.M. RADICELLA and E. FEICHTER (2002a): The data grid method to actualize empirical electron density models, in *Proceedings 10th International Ionospheric Effects Symposium*, edited by J. GOODMAN, 139-146.

LEITINGER, R., S.M. RADICELLA and B. NAVA (2002b): NeQuick for ITU-R: the product delivered and plans for improvements, in *Proceedings of the 2nd COST 271 Workshop*, 2-4 October 2002, Faro, Portugal.

LEITINGER, R., L. CIRAOLO, L. KERSLEY, S.S. KOURIS and P. SPALLA (2004): Relations between electron content and peak density: regular and extreme behaviour, *Ann. Geophysics*, **47** (suppl. to no. 2/3), 1093-1107 (this volume).

MALAN, D. and N. JAKOWSKI (2003): Comparison of radio occultation and ionospheric tomography observations over western Europe, in *Proceedings of the 3rd COST 271 Workshop*, 23-27 September 2003, Spetses, Greece.

RIEGER, M. (2002): Smaller scale electron content differences deduced from regional GPS data, in *Proceedings of the 2nd COST 271 Workshop*, 2-4 October 2002, Faro, Portugal.

RIEGER, M. and R. LEITINGER (2002): Assessment of TID activity from GPS phase data collected in a dense network of GPS receivers, *Acta Geod. Geophys. Hung.,* **37**, 327-341.

ŠAULI, P., J. BOCHNÍČEK, J. BOŠKA, L. CIRAOLO, P. HEJDA and S.M. RADICELLA (2003): Short-term variations of the ionospheric *F*-region measured during campaign HIRAC 2001 over Průhonice Observatory.

SPALLA, P., N. JAKOWSKI, A. WEHRENPFENNIG, P.S.J. SPENCER and C.N. MITCHELL (2002): Verification of CHAMP radio – Occultation observations in the onosphere using MIDAS, poster presented at the *1st CHAMP Science Meeting*, 22-25 January 2002, GFZ Potsdam.

STAMPER, R., J.L. LILENSTEN and N. JAKOWSKI (2004): Nowcasting, forecasting and warning for ionospheric propagation: supporting databases, *Ann. Geophysics*, **47** (suppl. to no. 2/3), 945-955 (this volume).

STOLLE, C., S. SCHLÜTER, N. JAKOWSKI and CH. JACOBI (2003): Electron density reconstructions using GPS measurements during HIRAC campaign in April 2001, in *Proceedings of the 3rd COST 271 Workshop*, 23-27 September 2003, Spetses, Greece.