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Ionospheric electron content: the European perspective

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Abstract
The electron content of the ionosphere is an important quantity which indicates overall ionization. It is measured by means of propagation effects on radio signals which penetrate the ionosphere. In Europe relevant investigations started after the launch of the first artificial satellites. Soon the necessity arose to organize international cooperation: the regional as well as the global geographical distribution of ionization parameters is important knowledge for any meaningful geophysical interpretation of ionization parameters. Despite the fact that international scientific Unions and Committees existed and had proven their usefulness and potential, private initiatives were taken to organize cooperation in the field of research based on transionospheric propagation effects. Only in 1971 three international groups joined together to form the «Beacon Satellite Group» as a «Working Party» of COSPAR. The «Beacon Satellite Group» still exists but is now a Working Group of URSI, the International Union for Radio Science. This contribution tries to summarize the European perspective with special emphasis on the long standing cooperation between the Istituto di Ricerca sulle Onde Elettromagnetiche (IROE) at Firenze and the Institut für Meteorologie und Geophysik of the University of Graz. Examples are given of important results.

Key words *upper atmosphere – ionosphere – electron content*

1. Introduction

The (vertical) electron content of the ionosphere, for which the acronym TEC is usual, is the number of free electrons above one square meter. Its geophysical definition is $I_{\perp} = \int_0^{h_c} N_e \, \mathrm{d}h$ with N_e: electron density (number density of free electrons), dh: height element, integration up to a «ceiling height» h_c which is typically between 800 and 2000 km.

Vertical electron content is a very good indicator for the overall ionization of the Earth ionosphere. Since in general many more electrons are found above the F layer ionization peak than below, the electron content can be considered an important quantity for investigations into the topside of the ionosphere which is not accessible with ground-based ionosondes.

Ionospheric electron content is measured by means of propagation effects which occur on radio signals which have traversed the ionosphere. Up to now the «normal» case is to have the source for the signals outside the ionosphere and the receiving equipment at the ground. Except for the occasional use of extraterrestrial sources and the use of signals transmitted from the ground and reflected by the surface of the Moon, the signal sources are on board artificial satellites.

The most important experimental methods are listed in table I together with the signal

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Table I. Experimental methods to measure ionospheric electron content (TEC) [c: carrier; m: modulation; LEO: orbit heights between 800 and 2000 km; GEO: geostationary satellite; GNSS: 12 h orbits (orbit heights around 20 000 km)].

Name	Signal components	Typical frequency bands	Satellites
Faraday Effect	Left- and right-hand circular components of one carrier	VHF	LEO, GEO,
Differential Doppler Effect (Carrier Phase Difference)	Two coherent carriers with large difference in frequencies	VHF/UHF, L-Band	LEO, GEO, GNSS
Group Delay (Modulation Phase Difference)	Identical and coherent modulations on two carriers	c: VHF/UHF, L m: 0.1 …10 MHz	(LEO), GEO, GNSS

components used (alternate names in parentheses).

There are three types of beacon satellites:

1) Satellites in orbits between about 800 km and 2000 km (Low Earth Orbit – LEO – satellites).

2) Geostationary (or near geostationary) satellites in heights of about 36 000 km.

3) The new type of navigation satellites in 12 h orbits with heights around 20 000 km (Global Positioning Satellite systems – GNSS – presently the US GPS system and its Russian equivalent GLONASS).

Originally the *Faraday Effect* was described as the influence of a magneto-plasma on the polarization plane of a linearly polarized radio signal: when the signal traverses the ionosphere the combined effect of the earth magnetic field and electron density along the ray produces the «Faraday rotation» of the polarization. A more general description is based on the «quasi-longitudinal» propagation of radio waves for which the characteristic polarizations are the left-hand and right-hand circular polarizations. A signal with an arbitrary polarization can be split into the two circular components.

For signal frequencies $f > 40$ MHz a good approximation for the square of the refractive indices is

$$n_{l,r}^{2} \doteq \frac{f_p^2}{f^2 \pm f\, f_g \left|\cos\theta\right|}$$

f_{p}: plasma frequency,

$$f_p^2 = \frac{e^2}{4\pi^2 m \varepsilon_0} = A N_e$$

f_{g}: gyrofrequency of free electrons,

$$f_g = \frac{eB}{2\pi m};$$

(e: electron charge [A s]; m: electron mass [kg]; ε_0: permittivity of free space [A s V^{-1} m^{-1}]; B: geomagnetic induction [T = V s m^{-2}]; Θ: angle between the phase propagation vector and the vector of geomagnetic induction; N_e: number density of free electrons [m^{-3}]; using SI-units: $A = 80.6$ m^3 s^{-2}).

In the geomagnetic north hemisphere the index l and the + sign correspond to the left-hand circular component, the index r and the – sign to the right-hand circular component. The approximation is not valid for propagation nearly perpendicular to the geomagnetic field vector. (It is valid outside the interval $\Theta = \pi/2 \pm \epsilon$; $\epsilon \simeq (3/2)\,(f / f_g)$ if $f \gg f_p$. Since in the atmosphere of the earth everywhere $f_g < 1.4$ MHz it follows $\epsilon < 1.2°$ for $f = 100$ MHz, $\epsilon < 0.12°$ for $f = 1$ GHz.) Assuming identical ray paths for the two circular components we obtain the «Faraday rotation»

$$\Omega = \phi_l - \phi_r = \frac{2\pi f}{c} \int_T^R (n_r - n_l)\, \mathrm{d}s.$$

From the dispersion formula follows

$$(n_r^2 - n_l^2) = (n_r - n_l)(n_r + n_l) \doteq$$

$$= \frac{f_p^2}{f^2}\left(\frac{1}{f-f_g} - \frac{1}{f+f_g}\right) = \frac{f_p^2}{f}\,\frac{2f_g}{f^2 - f_g^2}.$$

In a sufficient approximation $(n_r + n_l) \doteq 2$. Neglecting f_g^2 in the denominator we obtain

$$\Omega = \frac{2\pi}{c}\,\frac{1}{f^2}\int_T^R f_p^2\, f_g\,\mathrm{d}s =$$

$$= \frac{2\pi}{c}\,\frac{A}{f^2}\,\frac{e}{2\pi m}\int_T^R N_e B\left|\cos\Theta\right|\mathrm{d}s.$$

With $\mathrm{d}s = -\mathrm{d}h/\cos\beta$ ($\mathrm{d}h$: height element, $\beta = \beta(h)$: zenith angle of the transmitter along the ray path) and by taking a mean value for $(B\left|\cos\Theta\right| / \cos\beta)$ we gain

$$\Omega \doteq \frac{K_F}{f^2}\overline{\left(\frac{B\left|\cos\Theta\right|}{\cos\beta}\right)}\int_0^{h_c} N_e\,\mathrm{d}h = \frac{K_F}{f^2}\overline{M}I_\perp;$$

$$K_F = \frac{e^3}{4\pi^2 m^2 \varepsilon_0 c} = 47295.7\ \mathrm{m}^2\ \mathrm{s}^{-2}\ \mathrm{T}^{-1},$$

provided that the geomagnetic/geometric factor $\overline{M}$ is calculated for a suitable height («mean ionospheric height»). The «ceiling height» h_c is the height of the transmitting satellite, h_s ,in the case of satellites in orbits around 1000 km, but is a fixed height of 2000 km in the case of geostationary satellites (see Titheridge, 1972). (Because of the decreases of $B \cos\Theta$ and of N_e with height the contribution of the electrons above 2000 km is negligible if a «mean ionospheric height» is chosen around about 400 km for the geometric factor $\overline{M}$. The influence of the electrons above 2000 km remains less than 5%.)

The Faraday effect was first used for ionospheric research around 1956 on radio waves transmitted from the surface of the earth and reflected by the moon (see, *e.g.*, Browne *et al.*, 1956; Evans, 1956; Bauer and Daniels, 1958). Murray and Hargreaves had already published in 1954 the correct interpretation of «fadings» observed on lunar radio echoes as signatures of the Faraday effect. Bowhill (1958) hinted at the possibility to use satellite signals, Aitchison *et al.* (1959) published a few estimates for partial electron content in an international journal, Garriott was the first to provide a thorough theoretical assessment (1960a) and the first systematic results (1960b). The importance of geostationary satellite beacons for Faraday effect investigations was recognized by Garriott and Gordon Little (1960).

The *Differential Doppler Effect* needs two carriers transmitted phase-coherently (frequencies f_1 and f_2). For signal frequencies > 100 MHz one can use a further approximation to the dispersion formula, namely $n^2 = 1 - f_p^2 / f^2$ («quasi-isotropic» approximation) and $n = 1 - (1/2)(f_p^2 / f^2)$ («high frequency» approximation). Let $f_1 = p\,f_r$ and $f_2 = q\,f_r$ (p, q: integer numbers, f_r: reference frequency) then we can obtain a linear approximation to the plasma influence on carrier phase by measuring the phase difference $\Psi = \phi_2/q - \phi_1/p$, ϕ_1, ϕ_2 being the received phases of the two signals. In a sloppy terminology Ψ is called «Differential Doppler Effect». (The time derivative of Ψ is approximately proportional to the plasma influence on the Doppler shift.) Assuming the same ray path for the two signals we obtain

$$\Psi = \frac{2\pi f_r}{c}\int_T^R (n_2 - n_1)\,\mathrm{d}s =$$

$$= \frac{\pi}{c}\,\frac{A}{f_r}\left(\frac{1}{p^2} - \frac{1}{q^2}\right)\int_T^R N_e\,\mathrm{d}s.$$

We see that Ψ is proportional to «slant» electron content $\int_T^R N_e\,\mathrm{d}s$. Replacing again $\mathrm{d}s$ by $\mathrm{d}s = -\,\mathrm{d}h / \cos\beta$ we obtain

$$\int_\mathrm{T}^\mathrm{R} N_e\,\mathrm{d}s = \int_0^{h_s} \frac{N_e}{\cos\beta}\,\mathrm{d}h =$$

$$\overline{\frac{1}{\cos\beta}}\int_0^{h_s} N_e\,\mathrm{d}h \doteq G_D\,I_\perp.$$

Instead of the true mean value for $1/\cos\beta$ one uses an approximate «geometric factor» G_D which is the value of $1/\cos\beta$ in the «mean ionospheric height» h_i.

The Doppler effect was first used for ionospheric research around 1950 on radio signals transmitted from rockets (see, *e.g.*, Seddon, 1953). Soon after the start of the first artificial satellites several authors pointed to the possibility to make use of the ionospheric influence to the Doppler effect on satellite signals (compare, *e.g.*, Hibberd, 1958; Weekes, 1958; Al'pert, 1958, cited from Al'pert, 1965 and 1975). Ross (1960) demonstrated the derivation of electron content, but there were no immediate applications. It needed a substantial modification: Garriott and Nichol (1961) showed that carrier phase differences contain the ionospheric information directly and that there is no need to go through a numerical differentiation process to gain the ionospheric influence to signal frequency. De Mendonça (1962) published the first practicable evaluation procedure.

There are various possibilities to use the *Group Delay Effect* of which one can be described as follows: two carriers (frequencies f_1 and f_2) are amplitude modulated with a sine wave (frequency f_m). The modulations are phase coherent at the transmitting antennas. The modulation produces two sidebands for each carrier (frequencies $f_1 \pm f_m$, $f_2 \pm f_m$). Only one sideband is used, here we assume the lower. (Any method which produces four signal components with frequencies f_1, $f_1 - f_m$, f_2, $f_2 - f_m$ is equivalent.) Furthermore, we assume separate reception of the four signal components giving the received phases ϕ_1, ϕ_{1s}, ϕ_2, ϕ_{2s}, s indicating the phases of the lower sidebands. The following phase combination is proportional to «group delay»:

$$\Phi = (\phi_1 - \phi_{1s}) - (\phi_2 - \phi_{2s}) =$$

$$= \frac{2\pi}{c} \int_T^R (f_1 n_1 - f_{1s} n_{1s} - f_2 n_2 + f_{2s} n_{2s}) \, \mathrm{d}s.$$

Again approximating the dispersion formula by $n = 1 - (1/2)(f_p^2/f^2)$ we obtain

$$\Phi = \frac{\pi}{c} A \left(\frac{1}{f_1 - f_m} - \frac{1}{f_1} - \frac{1}{f_2 - f_m} + \frac{1}{f_2} \right) \int_T^R N_e \, \mathrm{d}s =$$

$$= \frac{\pi}{c} A f_m \left(\frac{1}{f_1 (f_1 - f_m)} - \frac{1}{f_2 (f_2 - f_m)} \right) \int_T^R N_e \, \mathrm{d}s.$$

Assuming $f_2 \gg f_1$ and $f_1 \gg f_m$ we see that F is proportional to «slant» electron content and approximately proportional to f_m / f_1^2.

The geostationary satellite ATS-6 gave a unique opportunity to use the Group Delay effect simultaneously with Differential Doppler and Faraday effect observations. The ATS-6 Radio Beacon Experiment (RBE) provided the only VHF/UHF coherent beacons especially designed for ionospheric and plasmaspheric research (Hargreaves, 1970): the difference between the Group Delay and the Faraday data gave the electron content of the plasmasphere (thermic plasma above 2000 km up to the plasmapause) (see Davies, 1980 for a review of ATS-6 RBE results).

2. Short overview on the history

The radio signals of the first artificial satellite, Sputnik 1, launched by the Soviet Union in 1957 during the International Geophysical Year (IGY) claimed the immediate attention of both amateurs and scientists. As far as it is known, in the Soviet Union it was the task for Yakov L. Al'pert's group at IZMIRAN to prepare the use of the Sputnik 1 radio signals for scientific research. By fortunate chance relevant research started in England immediately after the launch of Sputnik 1, too: the signals were received at the Cavendish Laboratory by the Radio Astronomers. For help they engaged Frank Hibberd who happened to be a guest scientist from Australia with the Ionosphere Research Group (Hibberd, 1997). Therefore one of the very first publications in scientific journals on plasma influences on satellite signals is of European origin (Hibberd, 1958).

The observation of propagation effects for the purpose of gaining ionospheric electron content had a quick start in the U.S.A., in Western Europe, in the Soviet Union and Eastern Europe and in Australia. South American countries and India followed soon. Since the ionization in our ionosphere has a strong inherent dependence on location, the need for cooperation was immediately seen. Interestingly enough it was first organized through personal relations and not through existing official channels, *e.g.*, the cooperation of the ionosonde stations. Since agency related Space Research had a strong interest in propagation effects, an «Eastern» cooperation was organized through Intercosmos and NASA sponsored the so-called S-66 Experiment which enabled wide participation because dedicated receivers could be purchased for a moderate price and because the participants obtained conversion tables enabling «pencil and paper» evaluation of chart recorded data. Another driving force for organized cooperation was connected to the geostationary communication satellites. It was quickly found out that their VHF navigation beacons could be used for Faraday effect observations. With a true geostationary satellite, evaluation of Faraday chart records can easily be carried out without computer assistance. One larger scale international cooperation was organized in the frame of the «Joint Satellite Study Group (JSSG)» founded and led by Jules Aarons, head of the beacon satellite research group of the U.S. Air Force Geophysics Laboratories (at this time called Air Force Cambridge Research Laboratories – AFCRL). Because of the U.S. Air Force sponsorship and because of links to NATO the JSSG could not establish any type of cooperation with the Intercosmos group. Some «Western» research groups were also reluctant to join JSSG officially, partly because they tried to maintain at least an exchange of information with «Eastern» groups. The center of this loosely knit third group which had no organizational frame was the Beacon Research Group of the Max-Planck-Institut für Aeronomie (MPAe) at Lindau/Harz, FRG headed by Gerd Hartmann. The impetus to form an all comprising organization under the auspices of a Scientific Committee came from Karl Rawer who happened to be chairman of relevant subdivisions of both URSI and COSPAR. Gerd Hartmann organized the first international scientific symposium which took place at MPAe Lindau/Harz in 1970 and brought acceptance for joining COSPAR. During the COSPAR Scientific Assembly 1971 at Seattle, U.S.A., the COSPAR Steering Committee on Satellite Beacon Activities was created. Later the Beacon Satellite Group became a Panel of COSPAR Working Group 1. This arrangement remained valid until 1981, the time of a major organizational reform for COSPAR. The Beacon Satellite Group (BSG) became Working Group G.12 «URSI Working Group on use of Beacon Satellite Transmission» of Commission G of the International Union for Radio Science (URSI). By this date the main advantage of COSPAR to provide a frame for «East-West» cooperation had ceased to «work» for the BSG. The fact that URSI is a scientific Union and not only a Committee is of advantage in «North-South» relations, especially in those which involve India and China. Presently the relevant Working Group G.2 has the title «Studies of the Ionosphere Using Beacon Satellites». It is important to note that the Beacon Satellite Group preserved its original form of (minimal) organization. It considers itself to be attached to URSI. It is interdisplinary both in the sense of scientific subjects and in the sense that it deals with science and engineering problems. The focus of the BSG are its Symposia which were held so far in distances of two to three years. The scientific content is published in Proceedings and Special Issues of international journals (see annex to list of references).

3. The European perspective

As far as it is known ionospheric research groups from the following European countries took up measurements of propagation effects on satellite radio beacons (in alphabetical order): Austria, Czechoslovakia, Finland, France, Germany (FRG and GDR), Greece, Italy, The Netherlands, Norway, Poland, Soviet Union, Spain, Sweden, United Kingdom.

Some degree of cooperation existed from the beginning but well separated into «West» and «East» with cross contacts via meetings at conferences. For example, it was possible to exchange some information on the occasion of the yearly «Kleinheubacher Tagung» as long as only one German Committee for URSI («Landesausschuß») existed. The Eastern cooperation was firmly and formally organised in the frame of «Intercosmos». At first «Western» cooperation was through participation in the S66 Experiment (using the LEO Beacon Explorers, preparation phase since 1962, launch failure of BE-A, successful launch for BE-B = Explorer 22 in October 1964, observation of BE-B and BE-C = Explorer 27 up to the end of 1969). Later and especially in view of the potential of geostationary satellite beacons a part of the «Western» cooperation was organized through the Joint Satellites Study Group (JSSG), led by Jules Aarons, head of the beacon satellite research group of the U.S. Air Force Geophysics Laboratories (at this time called Air Force Cambridge Research Laboratories - AFCRL). Otherwise European cooperation was rather informal and on a personal basis. One close cooperation which still exists was founded in 1965, namely that between the beacon satellite groups at Max-Planck-Institut für Aeronomie at Lindau/Harz, Germany and at the University of Graz.

In Europe and elsewhere ionospheric research with satellite radio beacons was making use of «Dedicated Experiments» and «Beacons of Opportunity». S66 belongs into the first group. A few other experiments followed. Other open to all experiments with organized participation were offered by the Spanish LEO INTASAT, a direct successor to the Beacon Explorers, the geostationary U.S. communication research satellite ATS-6 with its Radio Beacon Experiment (RBE, principal investigator: Kenneth Davies), and the geostationary Italian communication research satellite SIRIO with a VHF beacon under the surveillance of IROE Florence (compare Capannini *et al*, 1978, 1983a,b,c, 1987; Capannini and Spalla, 1980; Checcacci *et al.*, 1982).

In Europe several VHF beacons onboard geostationary satellites (or «drifting» satellites in geostationary heights) were used as Faraday beacons of opportunity and all types of navigation satellites were used as beacons for Differential Doppler and Group Delay measurements.

4. The cooperation between Florence and Graz

Close relations with direct exchange of information and opinions were established in 1969 between the late Pier Francesco Checcacci, leader of the Beacon Research Group at IROE Florence, Gerd Hartmann, head of the Beacon Group at MPAe Lindau, and the author of this contribution.

The original cooperation comprised exchange of information, of opinions, of data and research results but also common planning for future applications of satellite beacons. Cooperation between Graz and Florence intensified when the SIRIO radio beacon went in operation. It turned out that only three receiving stations took up continous observations of the SIRIO VHF Beacon: Florence, Graz and Neustrelitz/GDR. Thanks to a cultural exchange agreement on government level between Austria and the German Democratic Republic it was possible to establish official links between Institut für Meteorologie und Geophysik of the University of Graz and Satellitenbeobachtungsstation Neustrelitz which belonged to the Academy of Sciences of the GDR. Official cooperation of GDR institutions with Italian institutions was not possible and therefore Graz acted as an intermediary for exchange of information about SIRIO and for scientific cooperation which concentrated on studies of magnetic storm effects in ionospheric electron content. Later it was possible to obtain GDR blessing for cooperation on a personal basis between Norbert Jakowski (Neustrelitz), Paolo Spalla (Florence) and Erich Putz (Graz) (see, *e.g.*, Jakowski *et al.*, 1990a,b) The electron content data from the SIRIO observations made at Florence, Graz and Neustrelitz are included in a common data bank and were used for modelling both at Neustrelitz and at Graz (Putz *et al.*, 1992, 1993, Leitinger *et al.*, 1993, 1995).

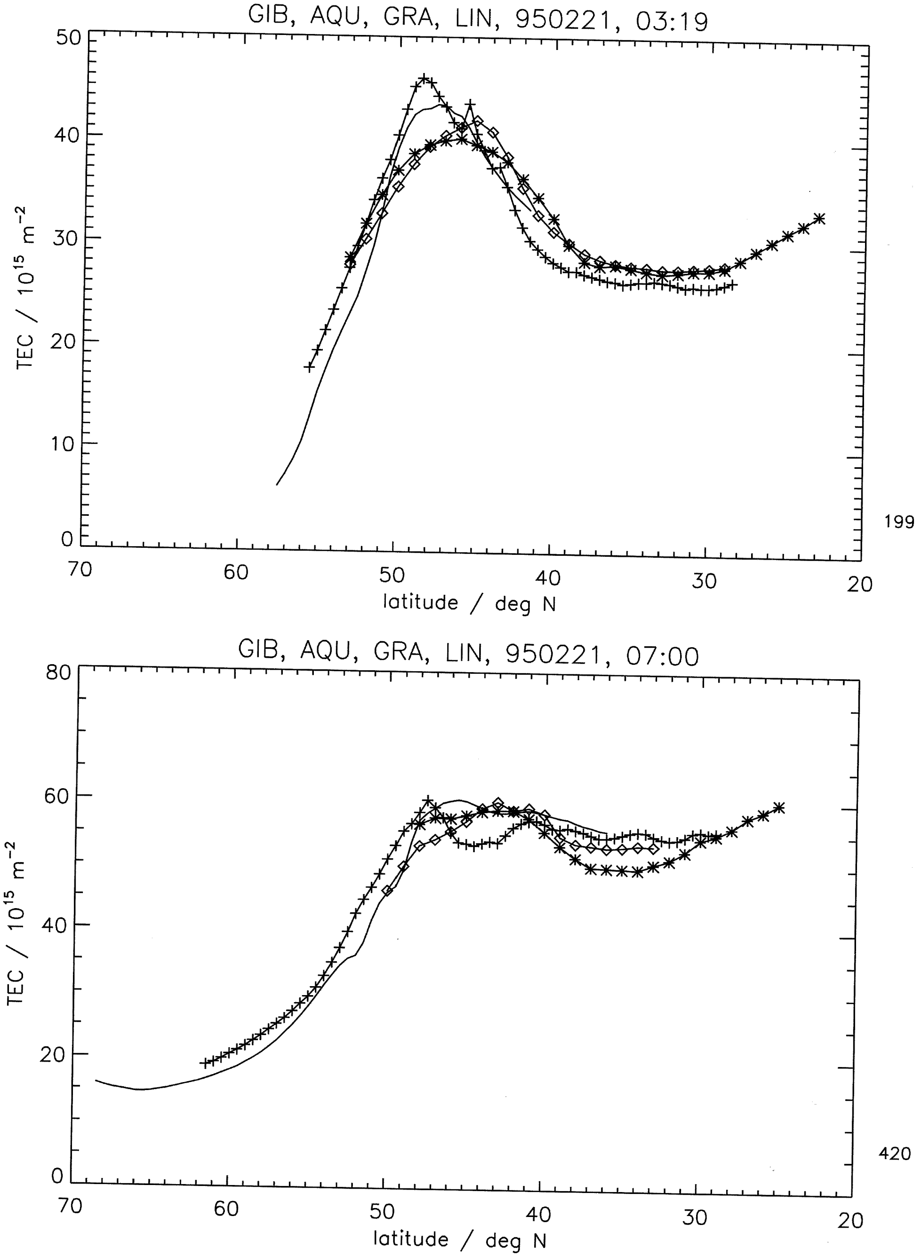

Fig. 1. Example for latitudinal profiles of vertical electron content from NNSS observations made from the stations GIBilmanna, L'AQUila, GRAz and LINdau. February 21, 1995, around 03:19 UT (top) and 07:00 UT (bottom). Electron content in units of $10^{15} m^{-2}$ *versus* geogr. latitude in deg. N (N to S). The top example shows a midlatitude maximum of electron content, possibly the signature of a «night-time increase». The minimum of the main trough is not seen because of a cut-off in the data from Lindau. It is indicated in the bottom example. The maximum has flattened out.

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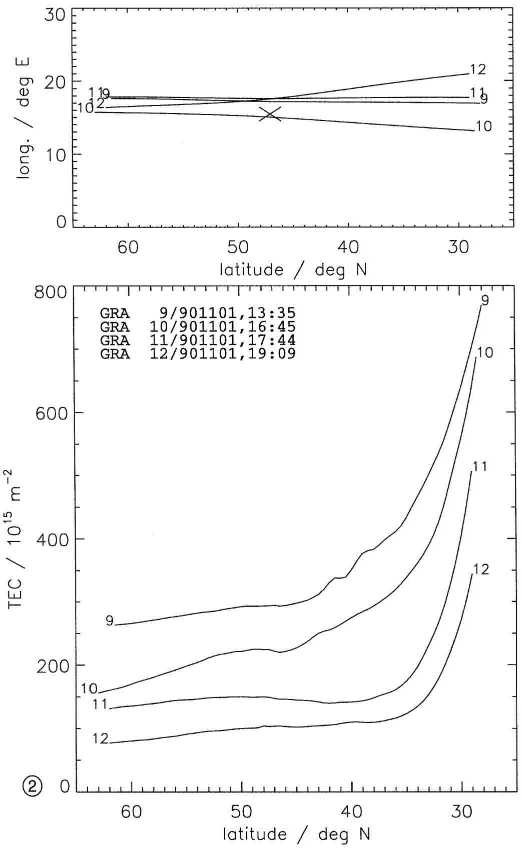

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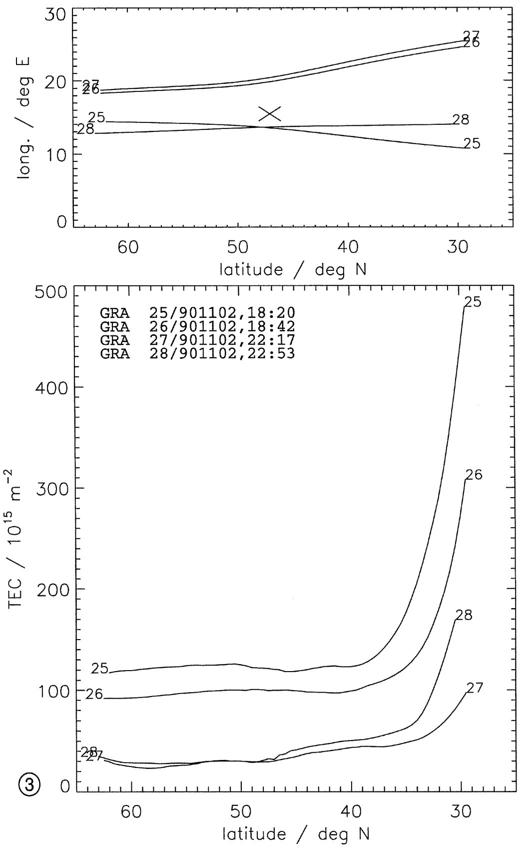

Fig. 2. Example for latitudinal profiles of vertical electron content from NNSS observations made at Graz demonstrating the potential of combined observations for times of high solar activity. Data from 1 November, 1990. Electron content in units of 10^{15} m^{-2} *versus* geogr. latitude in deg. N (N to S). Upper panel: traces of the ionospheric points (in 400 km height) in a geographic system. The figure shows clearly the importance of the equatorial anomaly even for «mid latitudes» (steep gradients and high TEC values). At times of high solar activity the northern crest of the equatorial anomaly should be visible from Gibilmanna.

Fig. 3. Example similar to fig. 2 but for the afternoon/evening of 2 November, 1990. The effect of the equatorial anomaly is even more prominent in the late than in the early afternoon because the mid latitude electron content has decreased.

Close cooperation between Florence, Graz, Neustrelitz and Lindau/Harz continues and presently concentrates on joint observations of the 150/400 MHz beacons of the polar orbiting NNSS satellites (see Guir and Weiffenbach, 1960) from Gibilmanna, L'Aquila, Graz, Neustrelitz and Lindau.

5. Examples for ionospheric electron content from the cooperation Florence-Graz

We concentrate on examples for latitudinal profiles of electron content from NNSS observations (figs. 1, 2 and 3) and to the combination of SIRIO data with peak electron density from

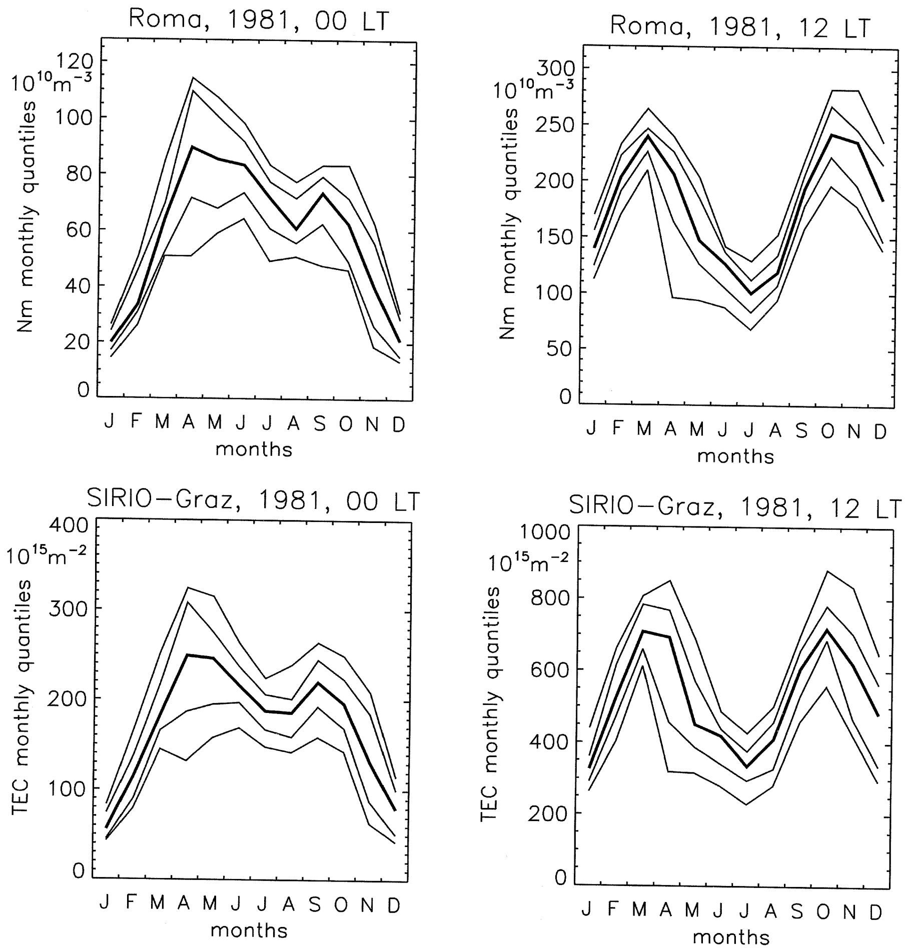

Fig. 4. Comparison of peak electron density N_m from f_0F_2 with electron content. Ionosonde station Rome, Italy (41.9°N, 12.5°E), electron content from Faraday observations made at Graz on the VHF beacon of SIRIO (latitude of the ionospheric point: 42.5°N). Data from 1981. Monthly quantiles for 0 LT and 12 LT. From bottom to top: lower deciles, lower quartiles, medians (heavy lines), upper quartiles, upper deciles.

the ionosonde station Rome (figs. 4 and 5). Examples for diurnal variations from the Faraday observations on geostationary satellites are also included (figs. 6 and 7).

6. Future aspects

Beacon Satellite Studies are currently in a transition state: the geostationary Faraday beacons have practically disappeared, at least for the European-African sector, and NNSS continues on a much reduced scale. The Global Positioning System (GPS) of the U.S. Air Force has found wide civilian applications and after several years of studies we have a good knowledge on its potential as a source of ionospheric data. The GPS satellites are in 12 h orbits (in heights around 20 000 km) and transmit two beacon signals with a pseudo random phase modula-

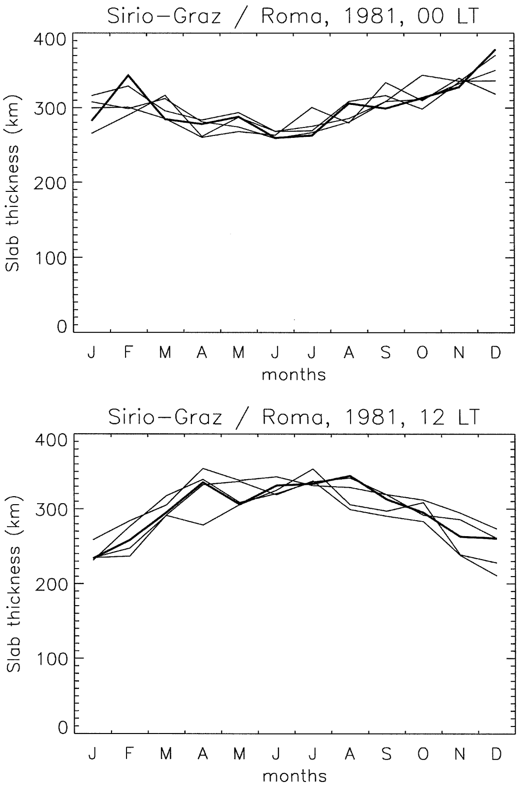

Fig. 5. Annual variation of equivalent slab thickness for 1981 from the combination of vertical electron content (TEC), measured by means of the Faraday effect on the VHF signal of SIRIO, received at Graz (latitude of ionospheric point 42.5°N) and peak electron density N_m from the ionosonde data of Rome (41.9°N, 12.5°E). Upper panel: 0 LT; lower panel: 12 LT.

tion. Carrier and side band reconstruction in the receiver gives beacon frequencies at 1227 and 1575 GHz and a sideband distance of 10 MHz allowing both Group Delay and Diff. Doppler evaluation for electron content but with a much lower resolution when compared against the «classical» beacons (see table II). It is important for the Beacon Satellite Community to succeed with the transition to GPS and its Russian equivalent GLONASS. Relevant studies in Europe have made an important contribution (*e.g.*, NNSS-GPS comparisons at Florence, see Ciraolo and Spalla, 1998a,b; adaptive modelling using GPS data at Neustrelitz, see Jakowski, 1998; Engler *et al.*, 1998).

There are two important new developments in Beacon Satellite Studies: the application of Tomographic Reconstruction techniques and the use of satellite-to-satellite radio links (see, *e.g.*, Leitinger *et al.*, 1996).

Proposals for tomographic reconstruction techniques using «Differential Doppler» data gained from the signals of polar orbiting navigation satellites began to appear around 1980. The reconstruction results are two dimensional electron density distributions, *e.g.*, in height and geographic latitude. In mid and high latitudes the height range from about 200 to 600 km is covered, in the surroundings of the equatorial anomaly the upper limit can be considerably higher (the range limits depend on the ratio of electron density to peak electron density). The horizontal range depends on the number and the spacing of the receiving stations. A typical range is 15 degrees.

In recent years several different reconstruction methods have found practical application and ionosphere tomography has reached the production stage. Most of the reconstruction methods fall into the categories of «pixel» methods (matrix reconstruction) or «model» methods (fitting of model parameters). All techniques suffer from the inherent problem that the data set available for the reconstruction is necessarily incomplete and therefore additional information («*a priori* knowledge») has to be used and it is not possible to select one reconstruction method only which should give the most plausible results under all conditions.

The newest developments in observation possibilities overcome the inherent weakness of this ground-based ionospheric tomography by using Global Navigation Satellite Systems (GNSS – the Global Positioning System GPS and/or its Russian equivalent GLONASS) and reception of the navigation beacon signals from satellites in low earth orbits. Shortly before Earth occultation of the signals the rays connecting transmitters and receivers are nearly horizontal and provide the information missing in ground based tomography. The method has been tried out with one satellite receiver (GPS/MET onboard of Microlab 1). The launch

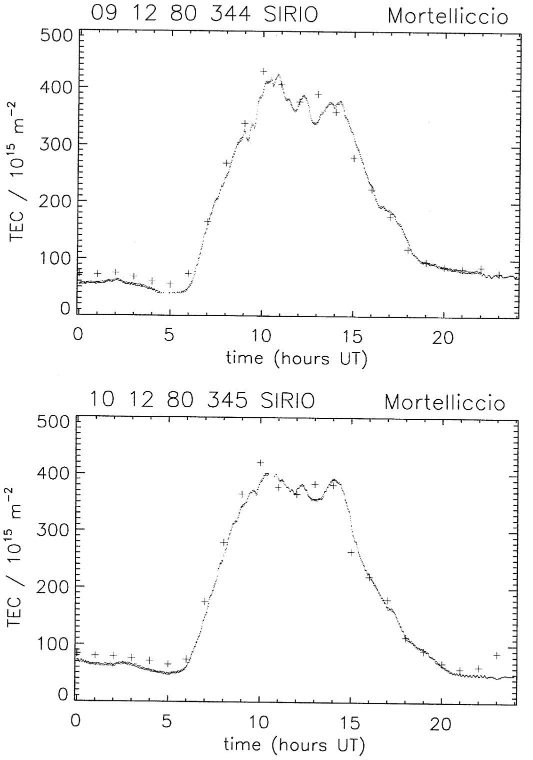

Fig. 6. Example for Faraday observations on the signals of the geostationary satellite SIRIO made at the Florence field station Mortelliccio (dots: one datum per minute) and Graz (crosses: hourly values). TEC in units of 10^{15} m^{-2} *versus* Universal Time in hours.

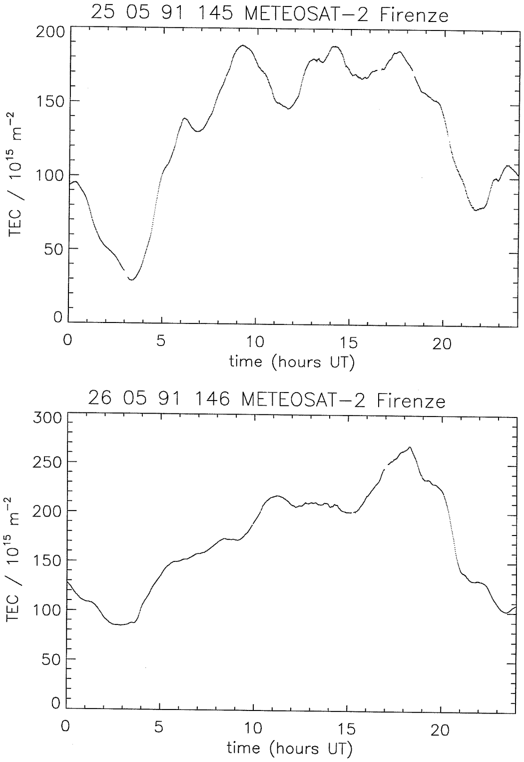

Fig. 7. Example for unusually strong Large Scale TID's in the Faraday observations made at Florence on the signals of the geostationary satellite METEOSAT-2 on 25 May, 1991. TEC in units of 10^{15} m^{-2} *versus* Universal Time in hours.

Table II. Sensitivity of propagation effects. E: «Effect» (F: Faraday, D: Diff. Doppler, G: Group Delay); f_1, f_2: carrier frequencies (coherent in case of Diff. Doppler); f_r: reference frequency (Diff. Doppler only); f_m: frequency of modulation (Group delay only, coherent on both carriers at transmitting antenna); $\Delta\phi/\Delta I_\perp$: sensitivity ($\Delta\phi$ relates to the phase difference as measured and as described above). Except for the Faraday Effect (line «F») all sensitivities relate to the case of an overhead position of the transmitter ($\beta = 0°$).
†For a «typical » mid latitude station using the signal of a geostationary satellite. The tabulated sensitivity is based on $B\,|\cos\Theta| = 40\,000$ nT and $\beta = 50°$.

E	f_1 MHz	f_2 MHz	f_r MHz	f_m MHz	$\Delta\phi/\Delta I_\perp$ $°/(10^{15}m^{-2})$	Remarks
F	$136^\dagger$	–	–	–	9.12	VHF Beacon of communication satellite
D	150	400	50	–	92.4	Navy Navigation Satellite System (NNSS)
D	1227	1575	1227	–	15.5	GPS (Global Positioning System)
G	140	360	–	1	2.21	Former ATS-6 Radio Beacon Experiment
G	1227	1575	–	10	0.13	GPS (Global Positioning System)

of several more experiments is expected for the immediate future and operational systems should appear at the turn of the millenium or shortly afterwards. These systems will be constructed to gain stratospheric and tropospheric temperature profiles. Since corrections are needed for the plasma influence there will be an ionospheric use as a by-product. The primary ionospheric information is horizontally averaged height profiles of electron density gained by means of classical inversion of the satellite-to-satellite electron contents. Tomographic reconstruction is one of the possibilities to add information on horizontal dependencies. In this case too Differential Doppler data from nearly meridional chains of receiving stations for the NNSS signals can play a major role provided that the system remains in operation long enough.

In view of both «meteorological» applications and of new civilian navigation systems arising (from navigation of sea and land vehicles to air craft landing) it is more important than ever to maintain the European ionospheric expertise and a high degree of cooperation. This cooperation exists, *e.g.*, in the frame of COST Telecommunications Actions (COST = Co-opertation in Scientific and Technological Research) and this author has no doubt that there is a continuing need to keep in operation the European Ionosonde network and to have links to receiving stations for GPS and GLONASS. After the demise of the geostationary Faraday beacons the ionosondes are the only instruments which provide time continuity with sufficient resolution for geographic grid points and therefore fulfil the important task of «monitoring» the state of the ionosphere. The new systems emerging will need information on storms, large scale Travelling Ionospheric Disturbances (TIDs) and on any unusual situation. The ionosonde network can provide just this information.

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