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VLBIONOS – Probing the Ionosphere by Means of Very Long Baseline Interferometry

Thomas Hobiger [1], Johannes Böhm [2], Harald Schuh [3]

[1] *Institute of Geodesy and Geophysics, Gußhausstraße 27-29, A-1040 Wien*
[2] *Institute of Geodesy and Geophysics, Gußhausstraße 27-29, A-1040 Wien*
[3] *Institute of Geodesy and Geophysics, Gußhausstraße 27-29, A-1040 Wien*

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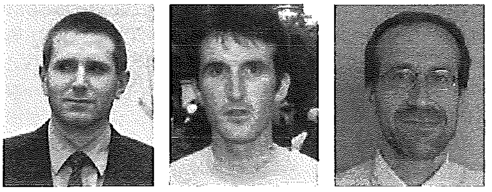
VLBIONOS – Probing the Ionosphere by Means of Very Long Baseline Interferometry

Thomas Hobiger, Johannes Boehm and Harald Schuh, Wien



Abstract

In geodetic Very Long Baseline Interferometry (VLBI) the observations are performed at two distinct frequencies (2.3 and 8.4 GHz) in order to determine ionospheric delay corrections. This allows information to be obtained from the VLBI observables about the sum of electrons (total electron content – TEC) along the ray path through the ionosphere. Due to the fact that VLBI is a differential technique, only the differences in the behavior of the propagation media over the stations determine the values of the observed ionospheric delays. However, in a first simple approach, an instrumental delay offset per baseline shifts the TEC measurements by a constant value. This offset is independent of the azimuth and elevation of the observed radio source and allows separation of the ionospheric parameters for each station from the instrumental delay offsets per baseline in a least-squares adjustment. In first tests of this method Fourier coefficients up to the 4th order plus a constant value and a linear trend were estimated to represent the vertical TEC (VTEC). Slant TEC (STEC) values are converted into VTEC values by a mapping function. A disadvantage of this approach is the assumption that these values are assigned to the station coordinates but not to the geographical coordinates of the intersection point of the ray path and the infinitely thin ionospheric layer. The precision of the estimated values is about +/– 5 to 7 TEC units (TECU). The results obtained from VLBI agree with a standard deviation of +/– 10 TECU with other techniques like GPS, rarely exceeding 20 TECU. A second approach, developed at the TU Vienna, using piece-wise linear functions (VTM – Vienna TEC model) was also tested.

Kurzfassung

Aufbau, Beschaffenheit, geographische und zeitliche Veränderungen der Ionosphäre (grob gesagt der Bereich der Erdhülle zwischen 50 km und 1000 km) sind für Meteorologen und Klimaforscher ein wichtiger Untersuchungsgegenstand. Aber auch für die Geodäsie spielt die Ionosphäre eine immer bedeutendere Rolle. Einerseits werden Signale im Radiofrequenzbereich durch die Ionosphäre derart abgelenkt bzw. verzögert, daß z.B. hochgenaue GPS-Messungen nur durch Beobachtung auf zwei Frequenzen möglich sind und es trotzdem während der ungefähr alle 11 Jahre auftretenden Perioden starker Sonnenaktivität zu spürbaren Genauigkeits- und Qualitätseinbußen der GPS-Ergebnisse kommt. Andererseits ist es heutzutage möglich, aus global verteilten GPS-Messungen wie sie z.B. im Rahmen des International GPS Service (IGS) durchgeführt werden, Informationen über den Zustand und die kurz- und langfristigen Veränderungen der Ionosphäre zu gewinnen. Im vorliegenden Artikel wird erstmals gezeigt, daß dies auch mit dem Verfahren der Very Long Baseline Interferometry (VLBI) möglich ist. Es sollen erste Ergebnisse präsentiert werden, die im Rahmen eines vom österreichischen Fonds zur Förderung der wissenschaftlichen Forschung (FWF) seit März 2003 unterstützten Forschungsprojekts erzielt wurden. Bei dem Verfahren der Radiointerferometrie auf langen Basislinien (VLBI) wird auf zwei unterschiedlichen Frequenzbändern (2.3 und 8.4 GHz) beobachtet, um die Laufzeitverzögerung zu bestimmen, die durch die Ionosphäre verursacht wird. Dadurch können Rückschlüsse auf den Gesamtelektronengehalt (TEC) entlang des Ausbreitungsweges der Welle gezogen werden. Allerdings lassen sich in einem einfachen Ansatz nur die Differenzen in der Beschaffenheit der Ionosphäre über den einzelnen Stationen bestimmen, und die Beobachtungen sind zusätzlich noch um einen durch instrumentelle Einflüsse hervorgerufenen konstanten Wert verfälscht. Da jedoch in unterschiedlichen Azimuten und Elevationen beobachtet wird, gelingt mittels spezieller Methoden durch eine Parameterschätzung nach der Methode der kleinsten Quadrate eine Trennung von den instrumentellen Einflüssen und somit eine Bestimmung der absoluten ionosphärischen Parameter. In ersten Analysen wurde der vertikale Gesamtelektronengehalt in Form von Fourieransätzen (bis Grad 4) geschätzt. Dabei wurde vereinfachend angenommen, daß alle Beobachtungen in Zenitrichtung durchgeführt wurden. Die innere Genauigkeit der VLBI-Ergebnisse wird zu +/– 5-7 TEC Units (TECU) geschätzt. Trotz der erwähnten Approximation stimmen die Ergebnisse auch mit denen von GPS innerhalb von +/– 10 TECU überein mit maximalen Abweichungen von 20 TECU. Ebenfalls erprobt wurde ein zweiter, an der TU Wien entwickelter Ansatz mit stückweise linearen Funktionen (VTM – Vienna TEC Model).

1. The Earth's ionosphere

The Earth's ionosphere is defined as that part of the upper atmosphere where free electrons occur in sufficient density to influence the propagation of electromagnetic radio frequency waves. The ionization depends primarily on the Sun and its activity. Ionospheric structures vary strongly with time corresponding to the sunspot cycle and seasonal and diurnal cycles and with geographical location (polar, auroral, mid- latitude and equatorial regions). Certain further ionospheric disturbances can be related to the Sun. The major part of the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most noticeable effect is seen as the Earth rotates with respect to the Sun. Ionization increases in the sunlit hemisphere and decreases on the shadowed side. Although the Sun is the largest contributor to the ionization, cosmic rays are the source of a small contribution, too.

The ionosphere is a dynamic system depending on many parameters, including acoustic motions of the atmosphere, electromagnetic emissions, and variations of the geomagnetic field. Any atmospheric disturbance affects the distribution of the ionization, and, because of its extreme sensitivity to atmospheric changes, the ionosphere can be used as a sensor of atmospheric events.

1.1. The structure of the ionosphere

1.1.1. Vertical profile of the ionosphere

Figure 1 gives schematically an overview of the vertical structure of the ionosphere, which can be vertically divided into four broad regions called D, E, F, and topside. These regions may be further divided into several regularly occurring layers, such as F1 or F2. The region between about 75 and 95 kilometers above the Earth, where the relatively weak ionization is mainly responsible for absorption of high frequency radio waves, is called the D region. The E region extends from 95 to 150 kilometers above the surface of the Earth. Other subdivisions isolating separate layers of irregular occurrence within this region are also labeled with an E prefix, such as the thick layer E2, and the highly variable, thin and sporadic Es layer. Ions in this region are mainly of type O_2^+ (ionized oxygen).

The F region is located about 150 kilometers above the E layer. In this region, the important reflecting layer F2 can be found. Other layers within this region are also described by the prefix F, such as a temperate latitude regular stratification F1. Ions in the lower part of the F layer are mainly of the type NO^+, in the upper part mainly O^+. The F layer is the region of primary interest for radio communications because this region is responsible for the reflection of radio waves that allows travel over great distances that cannot be achieved by direct radio waves due to the curvature of the Earth. Topside is the part of the ionosphere starting at the height of the maximum density of the F2 layer and extends upwards with decreasing density to a transition height where O^+ ions become less numerous than H^+ and He^+ ions. The transition height, which is usually above 1000 kilometers, varies by time but seldom drops below 500 kilometers at night or 800 kilometers in the daytime. Above the transition height the weak ionization has small influence on transionospheric radio signals.

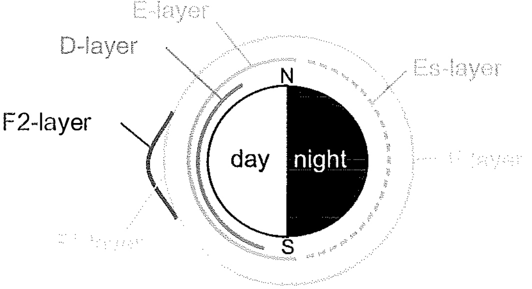


Figure 1: Ionospheric layers

1.1.2. Main geographical regions of the ionosphere

The ionosphere can be divided into two major geographical regions corresponding to the two principal regimens of magnetospheric circulation [1]: the low and mid latitude regions (less than 60° geomagnetic latitude) and the high latitudes. Figure 2 schematically shows these main geographic regions, although there is no well-defined boundary between these two parts. In the figure the day/night boundaries and the continents are represented for 12 h UT. The low latitude or equatorial region is characterized by high numbers of free electrons and by large spatial gradients. In this region the geomagnetic anomaly takes place. The mid latitude regions are those that present the more regular and predictable variations, although magnetic storms can cause nearly daily changes of about 30% in the total electron content (see section 1.2). The high latitudes or polar regions are characterized by spatial and temporal variations that are unpredictable. The reason is that in these regions the magnetic field intensity is three times larger than at the equator and the direction of its magnetic force is almost vertical. Therefore, solar wind particles that are mainly protons are accelerated down to very low altitudes, ionizing atmospheric atoms and molecules by collision.

spots are relatively cold regions of the Sun's photosphere. Due to the fact that their temperature is lower than that of the adjacent regions, they appear as dark areas in optical observations. Sunspots are associated with the most impressive events that take place on the Sun, the flares. These events occur more frequently dur-

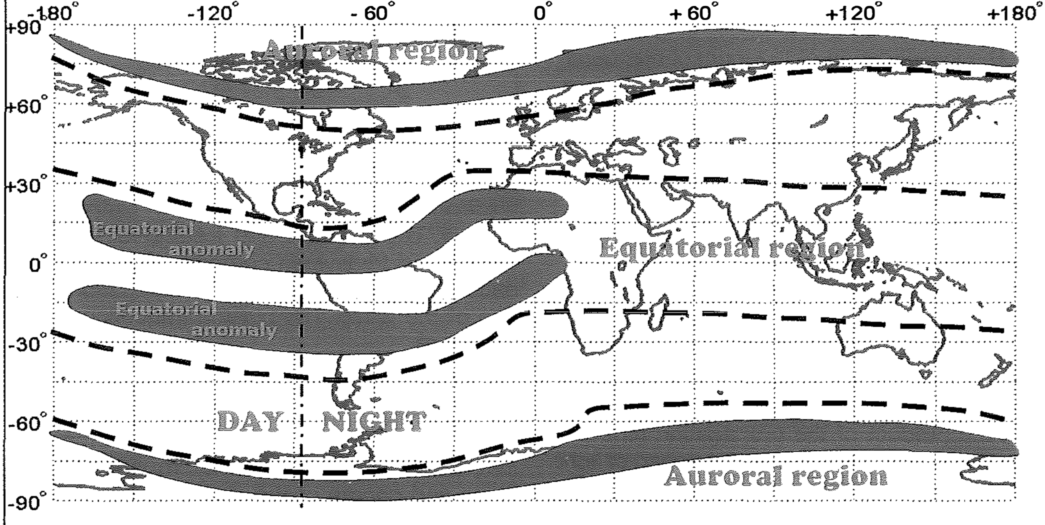


Figure 2: Main geographical regions of the ionosphere

1.1.3. Temporal variations

Every year the Sun, after crossing the equator from South to North or vice versa, reaches a maximum declination of about 23° in the solistices. This motion of the Sun, of which the most perceptible effect is the seasonal climatic change, produces in the ionosphere a variation of the free electron distribution from South to North of the equator or vice versa. This is the so-called seasonal variation. The most important ionospheric temporal variation is caused by the solar cycle, although along this cycle the radiation intensity does not fluctuate by more than 1%. The sunspot number (more precisely, the Wolf number, defined as $R = k(f + 10g)$ where f is the total number of sunspots, g is the quantity of sunspot groups, and k is a constant that depends on the sensitivity of the observational instrument) has been utilized as an indicator of solar activity. Historical records dealing with the sunspot numbers show a cycle with an average period of 11.1 years, with fluctuations running from 7 years for the shortest cycles up to 17 years for the longest periods. The most recent sunspot maximum happened in 2001/2002. Sunspots are relatively cold regions of the Sun's photosphere.

ing the solar cycle maxima, and they are less frequent during the minima. Additional quantities of protons, alpha particles, and ultraviolet and soft X-rays are emitted by the Sun and produce so-called magnetic storms. The X-rays immediately arrive at the Earth causing a rapid increase in the free electron density all over the illuminated hemisphere, which is known as sudden ionospheric disturbance. The other parts of the ejected matter arrive later and cause irregularities in the behavior of the ionosphere.

There are two other phenomena that have to be explained here: traveling ionospheric disturbances and scintillations. Traveling ionospheric disturbances are structures with a free electron density much greater than in the surrounding volume. Their size can vary from 50 to 500 km, and their velocity can reach several hundreds of kilometers per second with respect to the Sun-fixed coordinate system. This fact causes temporal variations which may last from a few minutes to several hours. Traveling ionospheric disturbances are more frequently found at mid-latitudes during the solar cycle maxima. Scintillation is a particular ionospheric disturbance consisting of a quick change in the free electron distribution, both in space and time, which affects the electromagnetic wave propagation within the ionosphere and produces a fast and irregular variation of its phase and amplitude. This effect is similar to the one that can be found when the brightness of a star is being observed through a turbulent atmosphere.

Ionospheric variations can happen on long time scales from years to decades and also on short time scales of a few hours or even seconds. The investigation of the ionospheric behavior is a quite important field of research, e. g. because the ionosphere influences the propagation characteristics of radio signals used in space geodetic techniques.

1.2. Impact on space geodetic techniques

One of the problems for all space geodetic techniques operating with electromagnetic waves is the determination of the propagation velocity of the signals. If these waves propagated in vacuum, the traveled distance would be just the product of the propagation time between emitter and receiver and the speed of light in vacuum. When signals travel through the ionosphere, the interaction between the electromagnetic field and the free electrons influences both the speed and the propagation direction of the signal, an effect known as ionospheric refraction [2]. The ratio between the propagation speed of a wave in vacuum and the propagation speed in a given medium is known as the refractive index

$$n = \frac{c}{v_{ph}}, \tag{1.1}$$

The phase velocity is related to the angular frequency and the wave number

$$v_{ph} = \frac{\omega}{k} \tag{1.2}$$

A medium is called to be dispersive when the wave number, and therefore the phase velocity, depends on the angular frequency of the wave. A signal consisting of a modulated carrier wave can be considered to be the result of superimposing a group of different wavelengths centered at the frequency of the carrier. In a dispersive medium the phase propagates with different velocity depending on its frequency. The group velocity v_g is given by:

$$v_g = \frac{d\omega}{dk} = v_{ph} + k\frac{dv_{ph}}{dk} \tag{1.3}$$

The group refractive index n_g of the medium is defined as

$$n_g = \frac{c}{v_g} = c\frac{dk}{d\omega} = n + \omega\frac{dn}{d\omega} \tag{1.4}$$

The Appleton-Hartree theory [2] allows the calculation of the refractive index for a single wave which propagates through a plasma (= ionized medium) according to

$$n^2 = 1 \frac{X}{1 - jZ - \left[\frac{Y_T^2}{2(1-X-jZ)}\right] \pm \sqrt{\frac{Y_T^4}{4(1-X-jZ)^2} + Y_L^2}} \tag{1.5}$$

where

$$j^2 = -1, X = \frac{\omega_p^2}{\omega^2}, Y_L = \frac{\omega_{SL}^2}{\omega^2}, Y_T = \frac{\omega_{ST}^2}{\omega^2}, Z = \frac{\omega_c^2}{\omega^2}, \tag{1.6}$$

In these equations ω represents the carrier frequency, ω_p is the frequency ω_p of the electron plasma, ω_s the synchrotron frequency of the electrons, and ω_c the so-called collision frequency. The indices L and T stand for the longitudinal and transverse components of the magnetic field with respect to the propagation direction of the wave. The plasma frequency can be written as

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \tag{1.7}$$

where N_e is the free electron density in the medium, ε_0 the vacuum permitivity, m_e and e are the mass and charge of the electron. Therefore the plasma frequency ω_p in the ionosphere is approximately $5 \cdot 10^7\ s^{-1}$. The synchrotron frequency in the ionosphere is proportional to the Earth's magnetic field and inversely proportional to the mass of an electron

$$\omega_s = \frac{eB}{m_e} \tag{1.8}$$

The synchrotron and collision frequencies are much smaller than the carrier frequencies of space geodetic techniques such as VLBI, GPS, GLONASS, DORIS, and TOPEX/POSEIDON. Neglecting these two values, the Appleton-Hartree formula can be reduced to

$$n \approx \sqrt{1-X} = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} = 1 - \frac{1}{2}\left(\frac{\omega_p}{\omega}\right)^2\left[1 + \frac{1}{4}\left(\frac{\omega_p}{\omega}\right)^2 + \ldots\right] \tag{1.9}$$

Dropping the terms of orders higher than $\left(\frac{\omega_p}{\omega}\right)^2$ we obtain a new approximation

$$n \approx 1 - \frac{1}{2}\left(\frac{\omega_P}{\omega}\right)^2 = 1 - \frac{1}{2}\frac{N_e e^2}{\varepsilon_0 m_e \omega^2} = 1 - \frac{40.28 N_e}{f^2} \tag{1.10}$$

where is f the carrier frequency expressed in Hz ($\omega = 2\pi f$). Using this result the group refractive index n_g can be determined by

$$n_g \approx 1 + \frac{1}{2}\frac{N_e e^2}{\varepsilon_0 m_e \omega^2} = 1 + \frac{40.28 N_e}{f^2} \tag{1.11}$$

Now we can calculate the carrier phase delay, d_{ph}, to obtain the influence of the ionized medium on the propagation delay, expressed in SI units (meters)

$$d_{ph} = \int_S (n_{ph}-1)dS = -\frac{40.28}{f^2}\int_S N_e dS = -\frac{40.28 \cdot 10^{16}}{f^2} STEC \quad (1.12)$$

The integral of the electron density along the signal path is usually called (Slant Total Electron Content). This quantity can be interpreted as the total amount of free electrons in a cylinder with a cross section of 1 m^2 of which the axis is the slant signal path. is measured in Total Electron Content Units (TECU), which is equivalent to 10^{16} electrons $\cdot$ m^{-2}. The effect of the ionized medium on group propagation can be expressed by

$$d_g = \int_S (n_g-1)dS = \frac{40.28}{f^2}\int_S N_e dS = \frac{40.28 \cdot 10^{16}}{f^2} STEC \quad (1.13)$$

The last two expressions show how the electron content in the ionosphere can influence measurements ranging from outer space to Earth-based stations. If the behavior of the ionosphere is known, these effects can be computed and can be used to correct measurements on radio frequencies. If ionospheric parameters are not available, group delay observations have to be carried out on two different frequencies,

$$d_1 = d_0 + \frac{const}{f_1},\ d_2 = d_0 + \frac{const}{f_2} \quad (1.14)$$

where d_0 is the distance in vacuum and const = $40.28 \cdot 10^{16}$ STEC. Combining the two equations (1.14) yields to the so-called ionosphere-free linear combination

$$d_0 = d_1 \frac{f_1^2}{f_1^2 - f_2^2} - d_2 \frac{f_2^2}{f_1^2 - f_2^2} \quad (1.15)$$

Thus, observing at two different radio frequencies allows the elimination of ionospheric influences.

2. Using space geodetic techniques to probe the ionosphere

2.1. GPS and the ionosphere

The NAVigation Satellite Timing and Ranging Global Positioning System (NAVSTAR GPS or shortly GPS) operates on two different frequencies (f_1, f_2) which are derived from the fundamental frequency f_0 = 10.23 MHz

$$f_1 = 154 \cdot f_0 = 1575.42\,MHz,\ f_2 = 120 \cdot f_0 = 1227.60\,MHz \quad (2.1)$$

Both code and phase measurements are affected by the dispersive behavior of the ionosphere, but with different leading signs which can be assigned to equations 1.12 and 1.13. Besides the ionosphere-free linear combination which eliminates the influence of the ionosphere, the so-called geometry free linear combination (also called L4-combination)

$$d_4 = d_1 - d_2 \quad (2.2)$$

allows an investigation of the total electron content along the ray path [3]. This term contains only the slant total electron content and the satellite and receiver differential code biases (DCBs), which are interpreted as the differential, inter-frequency hardware delays [4]. Calculating the geometry free linear combination, using both code and phase measurements, allows separation of the DCBs from the STEC values in a least-squares adjustment process.

The International GPS Service (IGS) has initiated a working group for the development of global ionospheric gridded data representing the total electron content over the whole globe. Several analysis centers deliver their results of vertical TEC values (VTEC) and DCBs in the IONospheric Exchange (IONEX) format [5], which represents the ionosphere as an infinitesimal shell in time intervals of two hours. Currently discrepancies exist in the solutions of the different analysis centers, and a combined solution is still missing [6].

2.2. A new field of research – ionospheric investigations by geodetic VLBI

2.2.1. How VLBI works

Very Long Baseline Interferometry (VLBI) is a space geodetic technique that allows measurement of distances of thousands of kilometers between stations of a global network with an error of a few millimeters. Radio signals from extragalactic radio sources (quasars or radio galaxies) are observed that have traveled several billion light years to the Earth. The VLBI technology provides precise station coordinates, and repeated measurements covering many years reveal plate tectonic rates and small changes in the Earth rotation with high accuracy. Radio sources are located almost infinitely far from the Earth, and the radio waves that leave these objects reach the Earth as plane wave fronts. If the signals are recorded at two radio telescopes at different positions, A and B (see figure 3), there is a time difference in receiving the same signal. This time difference, also called „delay", is measured with an accuracy of the order of 10^{-11} seconds. The product of this delay and the velocity of the radio wave (equal to the velocity of light) is called path difference, which allows calcula-

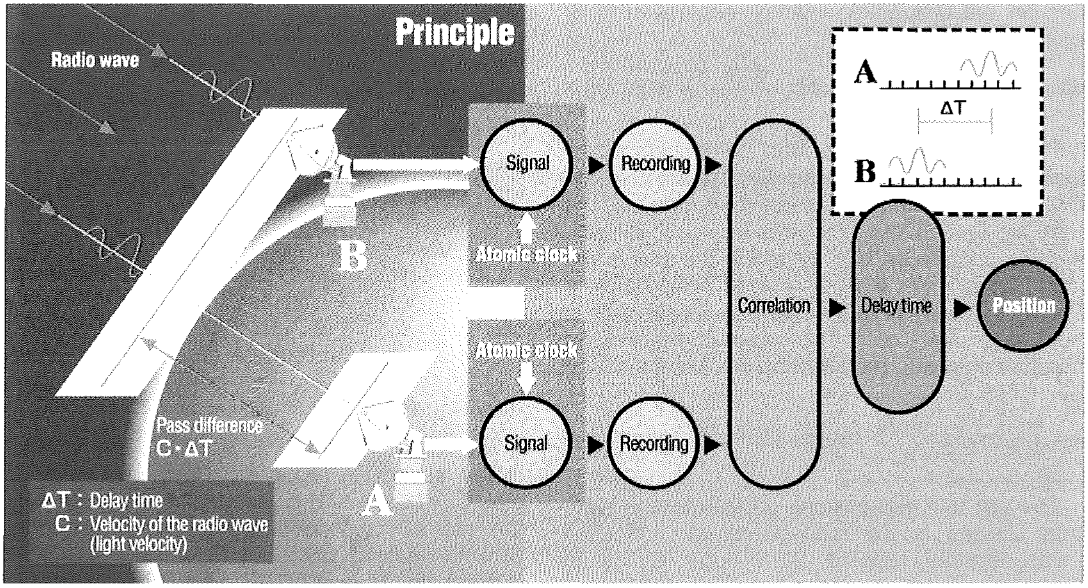


Figure 3: Principle of VLBI

tion of the distance between the two stations in the direction of the radio wave. The relative positions of A and B can be calculated by consecutively conducting these measurements in three or more directions.

2.2.2. VLBIonos

The project 'VLBIonos', supported by the Austrian Science Fund (FWF), started on March 1st, 2003, and aims at the investigation of the ionosphere using geodetic VLBI. VLBI observations are performed at two different frequencies (2.3 and 8.4 GHz, S- and X-band) in order to determine the ionospheric delay. As shown by 7] this information can be used to model the ionosphere above each station. It has to be mentioned that only the differences in the ionospheric delay between the two stations are measured. Unfortunately, instrumental offsets at each station bias these measurements, which leads us to

$$\tau_{model}(t) = \tau_{ion,1}(1) - \tau_{ion,2}(t) + \tau_{offset,1} - \tau_{offset.2} \qquad (2.3)$$

The ionospheric delay at X-band over station can be modeled as

$$\tau_{ion,i}(t) = \frac{1.34 \cdot 10^{-7}}{f_x^2} \cdot S(E_i) \cdot VTEC_i(t) \qquad (2.4)$$

where

$$S(E_i) = \frac{1}{\cos\left\{\arcsin\left[\frac{R\cos E_i}{R+h}\right]\right\}} \qquad (2.5)$$

and $VTEC_i(t)$ represents the vertical TEC value at the intersection point of the ray path with the infinitesimally thin ionospheric layer assumed to be at the height h. The radius of the (spherical) Earth is abbreviated with R. Under the assumption that horizontal gradients in the ionosphere can be neglected within a range of about 300 kilometers, $VTEC_i(t)$ can be assigned to the geographical coordinates of the VLBI station. In our first investigation we concentrate on modeling the behavior of the ionosphere over the stations by two different approaches.

- Model proposed by Kondo [7]
  In this model $VTEC_{Kondo}(t)$ for station i and time t is calculated as suggested by Kondo [7] using a constant offset, sine and cosine functions, and a daily rate

$$VTEC_{Kondo,i}(t) = a_{i0} + \sum_{k=1}^{4}\left[a_{ik}\cos\left(\frac{kt\pi}{12}\right) + b_{ik}\sin\left(\frac{kt\pi}{12}\right)\right] + c_i t \qquad (2.6)$$

- Vienna TEC Model (VTM)
  In this model $VTEC_{VIENNA}(t)$ is calculated as a piece-wise linear function

$$VTEC_{VIENNA,i}(t) = offset_i + rate_{i1}(t_1 - t_0) + rate_{i2}(t_2 - t_1) + \ldots + rate_{in}(t_n - t) \qquad (2.7)$$

  and $t \le t_n$

After calculating the partial derivatives

$$\left(\frac{\partial VTEC_{Kondo,i}}{\partial a_{ij}}, \frac{\partial VTEC_{Kondo,i}}{\partial b_{ij}}, \frac{\partial VTEC_{Kondo,i}}{\partial c_i} \text{ or } \frac{\partial VTEC_{VIENNA,i}}{\partial offset_i}, \frac{\partial VTEC_{VIENNA,i}}{\partial rate_{ij}}\right)$$

a least-squares adjustment allows separation of the VTEC values from the constant instrumental offset $\tau_{offset,i}$. This is possible because observations are performed at different elevation angles which prevents the design matrix from becoming singular. The VTM approach also includes constraints on the VTEC-rate of about +/− 30 TECU per hour for two reasons: to get physically reasonable values and to get a non-singular design matrix even if there are gaps in the data.

3. Results

3.1. Ionospheric values and maps derived by GPS

Data relevant to this work stored in IONEX format on the IGS web server are provided by the following analysis centers:

- Center for Orbit Determination in Europe (CODE), University of Berne, Switzerland,
- Geodetic Survey Division of Natural Resources Canada – formerly Energy, Mines and Resources Canada (EMR), Ontario, Canada,
- European Space Operations Centre (ESOC) at the European Space Agency (ESA), Darmstadt, Germany,
- Jet Propulsion Laboratory (JPL), Pasadena, U.S.A.,
- Group of Astronomy and Geomatics, Universidad Politecnica de Catalunya (gAGE/UPC), Barcelona, Spain.

Figure 4 shows VTEC values for Kokee Park (Hawaii) as calculated by the different analysis centers. Figure 5 shows the CODE solution (CODE, http://www.aiub.unibe.ch/ionosphere.html, [8]) for March 4th, 2003, 14:00 UTC plotted as a (two-dimensional) contour plot.

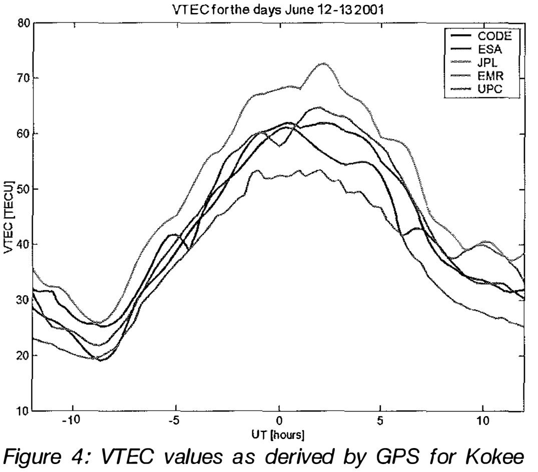


Figure 4: VTEC values as derived by GPS for Kokee Park (Hawaii).

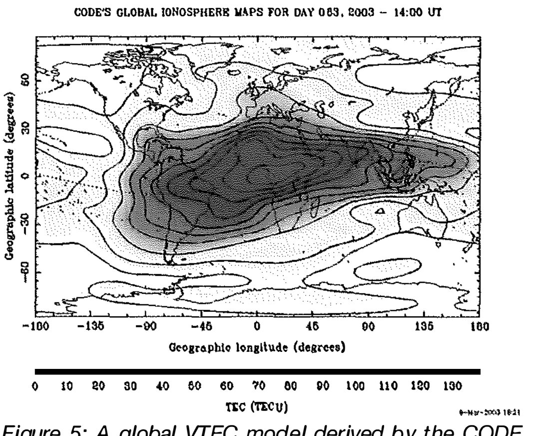


Figure 5: A global VTEC model derived by the CODE analysis center for March 4th, 2003, 14:00 UTC.

3.2. Values derived by VLBI

3.2.1. Results of the Kondo approach

Figure 6 shows VTEC values determined from the NEOS-A session on January 16th, 2001 (all contributing stations of this session are plotted in figure 7) over the station Fortaleza (solid line) compared to TEC numbers derived by CODE GPS solution (dashed line). In figure 8 the amplitudes and their precision of the harmonic terms, i.e. for periods of 24h, 12h, 8h, and 6h, for all stations involved in this experiment are plotted according to this model approach. Stations that are closer to the equator show larger amplitudes for daily periods. These results agree with the properties of the geographic regions as mentioned above. The correlation between amplitude and pole distance (90° minus absolute latitude)

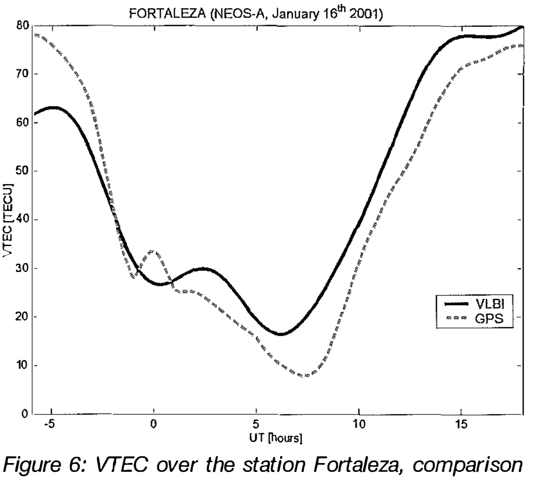


Figure 6: VTEC over the station Fortaleza, comparison between VLBI (Kondo approach) and GPS.

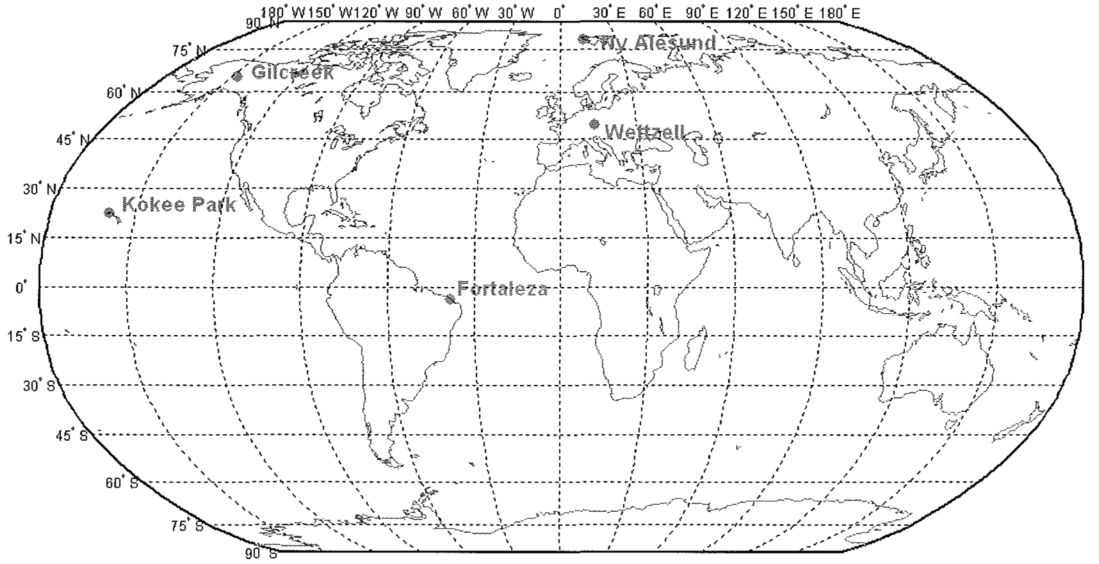


Figure 7: NEOS-A session on January 16th, 2001 – contributing stations

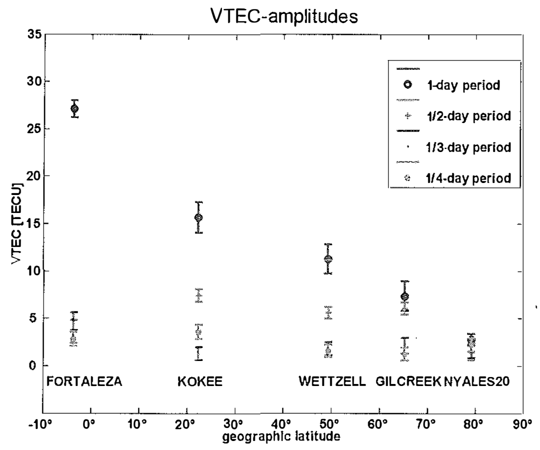


Figure 8: Amplitudes and their precision from the NEOS-A session on January 16th, 2001.

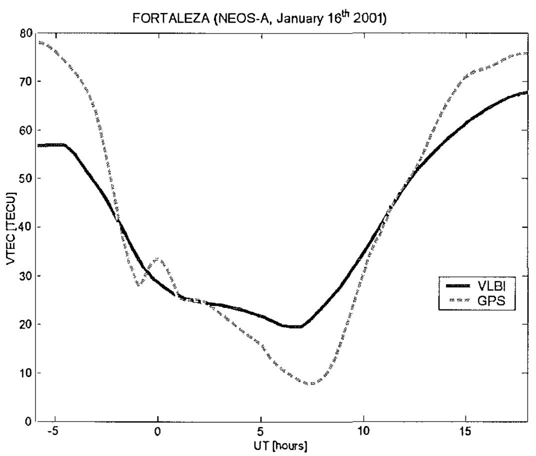


Figure 9: VTEC over station Fortaleza, comparison between VLBI (VTM approach) and GPS.

cannot be detected for sub-daily periods. From the error bars of the amplitudes we estimate the overall precision of the VLBI TEC values to +/– 5 to 7 TECU.

3.2.2. Results of the VTM approach

The same session as in 3.2.1 was analyzed now with the VTM. Two examples of the results are given here for the stations Fortaleza (figure 9) and Gilcreek (figure 10) compared to the CODE GPS computations.

For stations Fortaleza and Gilcreek generally good agreement can be seen between values derived by GPS and VLBI. The Fortaleza plot shows that the values derived by VLBI are much smaller during high ionospheric activity, i.e. around noon, local time.

3.2.3. Comparison of the VTM approach with all IGS analysis center solutions

The solutions of all analysis centers are plotted in figure 11 as dashed lines and compared with the VTM result (thick line). If for all stations in the NEOS-A network (the same as in 3.2.1 and 3.2.2) the differences between the VLBI and GPS solutions are calculated every 0.1 hour and all values are plotted in one histogram figure 12, is obtained. This should give an idea about the accuracy of the VTM approach.

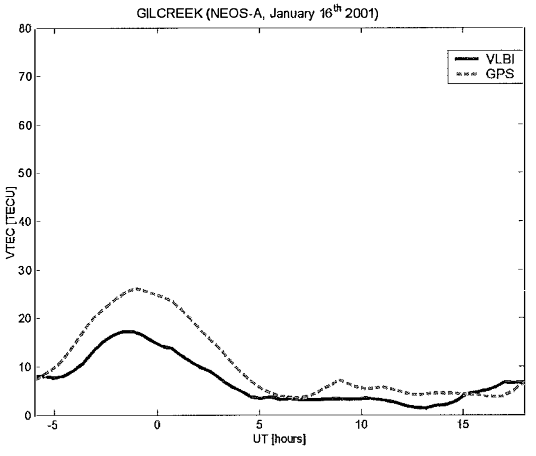


Figure 10: VTEC over station Gilcreek, comparison between VLBI (VTM approach) and GPS.

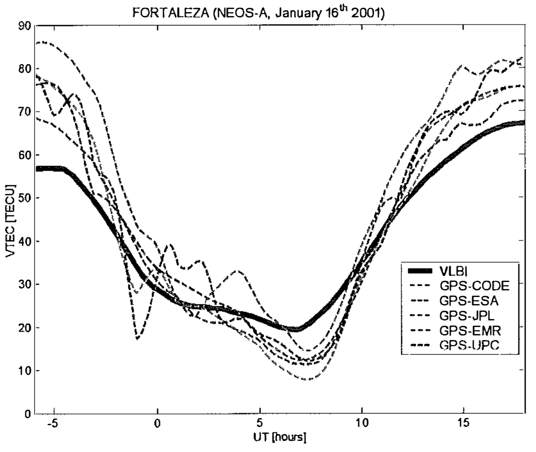


Figure 11: VTEC over station Fortaleza, comparison between VLBI (VTM approach) and GPS solutions of all analysis centers.

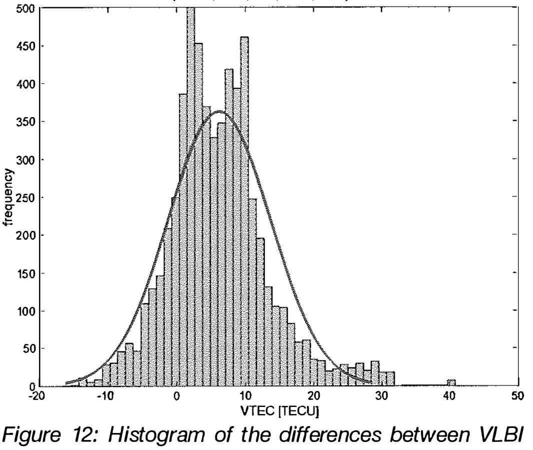


Figure 12: Histogram of the differences between VLBI and GPS solutions.

A normal distribution curve was fitted to the histogram which shows a mean difference ('bias') between VTEC values derived by VLBI and GPS of about 7 TECU.

4. Outlook

First investigations have shown that VLBI is able to deliver information about the spatial distribution and temporal variation of the ionosphere. Further research should deal with the problem that the calculated TEC values are not vertically located above the station. Another proposed goal of this project is the development of ionospheric maps like those published by IGS (IONEX). Since differences between VTEC values derived by GPS and TOPEX/Poseidon are usually in the range of 3 to 7 TECU, further comparisons with other techniques which deliver ionospheric information are necessary to evaluate which techniques are most accurate.

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Contact

Dipl.-Ing. Thomas Hobiger, Dipl.-Ing. Johannes Boehm, Univ.-Prof. Dr.-Ing. Harald Schuh: Abteilung Höhere Geodäsie, Institut für Geodäsie und Geophysik, TU Wien, Gusshausstraße 27–29, A-1040 Wien. email: thobiger@luna.tuwien.ac.at, jboehm@luna.tuwien.ac.at, hschuh@luna.tuwien.ac.at