# VLBI AND IONOSPHERE

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**ABSTRACT**

The terrestrial ionosphere is an obstacle to precise geodetic measurements using the VLBI technique, because radio signals propagated through the ionosphere undergo frequency dependent excess delays. These excess delays are conventionally removed by receiving at dual S-band (2GHz) and X-band (8GHz) frequencies. If the total electron content (TEC) along the ray paths from a radio source to each VLBI station is given by any other methods, the excess delays become calculable so as to calibrate the measurements. It is therefore possible to employ a single-frequency-band receiving system as a VLBI station. TEC obtained by GPS signal measurements can apply for this purpose with an accuracy of about 0.1ns (in case elevation angle larger than 30 degree) in terms of X band excess delay. On the other hand, dual band VLBI measurements is applicable to research the ionosphere itself. Dual-band VLBI data since 1984 have been analyzed to estimate the TEC and have been compared with the TEC computed from the international reference ionosphere model (IRI90). The results of comparison reveal the defect of the IRI model at geomagnetic latitude > $40^{o}$.

## 1. Introduction

This paper will introduce the two different aspects of the ionosphere regarding its relation to VLBI. One is the ionosphere as an obstacle for precise geodetic measurements. Radio signals propagated through the ionosphere suffer frequency dependent excess delays due to the dispersive medium. These excess delays are removed by receiving signals at dual frequency bands (usually 2GHz and 8GHz). An alternative method using the GPS measurements will be briefly introduced (see the paper by Kondo and Imae [1992] for detailed procedure of correction and discussion).

The other is the ionosphere observed as a by-product of the dual-band VLBI measurements. The dual-band VLBI which receives signals at dual frequency bands implicitly contains the information about the TEC applicable for the study of the ionosphere itself. A method to estimate the TEC at each VLBI station from the dual-band VLBI measurements has been developed [Kondo and Hama, 1990; Kondo, 1991]. Accumulation of data for many years by the NASA Crustal Dynamics Project (CDP) and the International Radio Interferometric Surveying (IRIS) project makes it possible to carry out a statistical study of TEC with a sufficient reliability. Results of the statistical study will be represented here in contrast with the international reference ionosphere model.

## 2. Ionosphere as an Obstacle -- Correction Using GPS measurements

A GPS satellite radiates coherently modulated signals at dual frequencies, L1 (1.57542 GHz) and L2 (1.2276 GHz). By measuring the difference in arrival time of modulation signals between L1 and L2, we can get the TEC along the ray path to the satellite. However the directions to the GPS satellites are usually different from those to radio stars observed by VLBI. Therefore it is necessary to project the observed TEC to any other desired directions along with an interpolation in the time domain for utilizing the GPS measurements to the VLBI ionospheric corrections. To perform this projection effectively, observed slant TEC is first converted to vertical (zenith) TEC at an intersection of line of sight and the ionosphere. The position of the intersection can be expressed by the time(UT)-latitude coordinates referred to a station. Then the distribution of vertical TEC on the UT-latitude coordinates is estimated for each station. Once the distributions of TEC on the UT-latitude planes are given, we can easily calculate the TEC in the directions of radio stars (see Kondo and Imae [1992] for detail). Fig.1 represents an example of TEC distribution on the UT-latitude planes for Minamitorishima (Marcus) station on July 3, 1991.

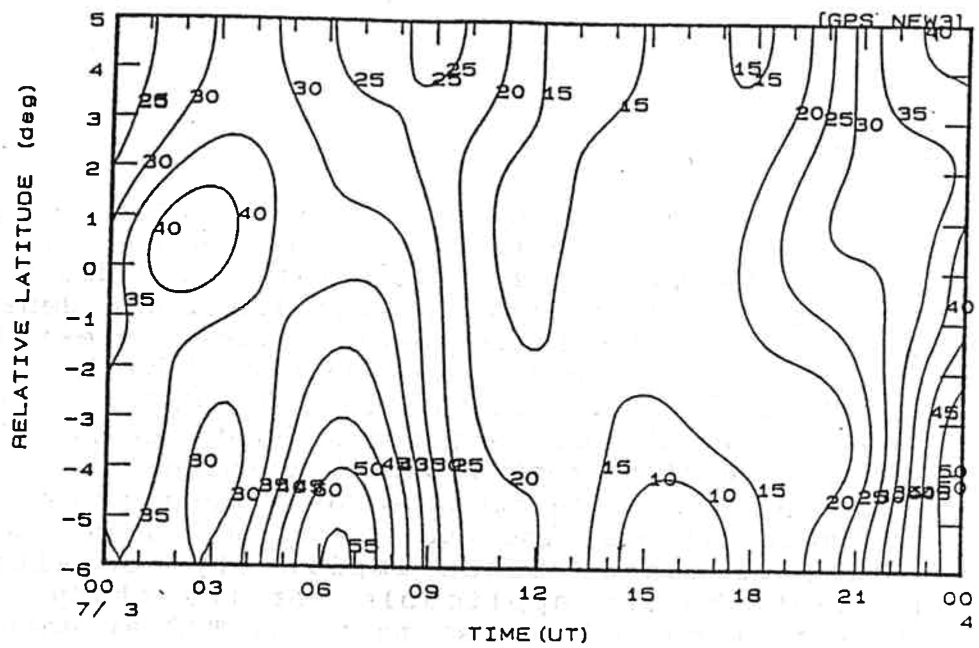


Fig.1 Contour plot of TEC distribution on UT-latitude plane obtained from the GPS measurements at Minamitorishima (Marcus) station on July 3, 1991. Latitude is relative latitude and unit of TEC contour is $10^{16}$el/m$^2$.

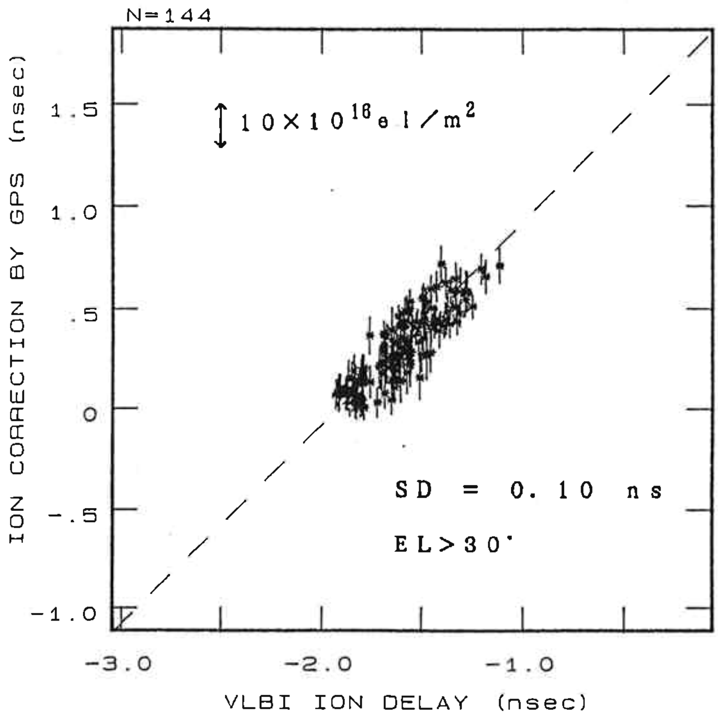


Fig.2 Comparison of calculated ionospheric excess delays and observed ones for an experiment made on the Kashima-Minamitorishima (Marcus) baseline on July 3, 1991. Ordinate denotes excess delay at X band (8GHz) calculated from the GPS measurements and abscissa is that observed by the dual-band VLBI. Elevation angle is limited to be larger than 30°.

Ionospheric corrections calculated this way have been compared with those actually observed by the dual-band VLBI on the Kashima-Minamitorishima (Marcus) baseline (about 2000km length) to evaluate the feasibility. The comparison shows fairly good coincidence between them (Fig. 2). Scatter of residuals after linear fitting is about 0.1ns in terms of X band delay ($5x10^{16}el/m^2$ in TEC) for the range of elevation angle larger than 30°.

## 3. Ionosphere as a By-product -- Comparison with the Model

The differential TEC is a direct observable in the dual-band VLBI. However, absolute zenith TEC for each station become estimable when baseline length is longer than several thousand kilometer like an intercontinental baseline and a VLBI session lasts for at least 24 hours. In the estimation, the variation of TEC at zenith is modeled by a mathematical function of the Fourier series with one day component and its harmonics up to the 4th order and a liner term to the time. Each coefficient describing the model is fitted by using the least squares method for each station (see Kondo [1991] for detail).

The method is applied for the VLBI data acquired in the Mark-III data base at the Goddard Space Flight Center (GSFC) to investigate the long term statistics of the ionosphere. Total 1418 sessions since 1984 to 1991 are used for the TEC analysis. First, so-called "ion-correction" data are extracted from the data base to form the data files reduced in size. Then the TEC estimation procedure is executed for the data stored in the reduced files. Among stations included in the data base, seven stations, Kauai (Hawaii,USA), Kashima (Japan), Richmond (USA), Mojave(USA), Wettzell(German), Westford(USA), and Gilcreek(Alaska,USA), are used for the comparative study described below. TECs estimated this way are compared with the international reference ionosphere (IRI) which is an empirical model of ionospheric densities and temperatures (electron and ions) in the altitude range 50 km to 2000 km recommended for international use by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). As a height profile of electron density is given by the IRI model as a function of station position (longitude and latitude), time (month and local time), and relative sunspot number, the TEC is obtained by integrating over the altitude range. The latest IRI model (program and data file) is available from the National Space Science Data Center (NSSDC) computer at GSFC through the computer network. The IRI90 model [Bilitza, 1990] is used here. An example of density profile calculated by the IRI90 model is represented in Fig.3.

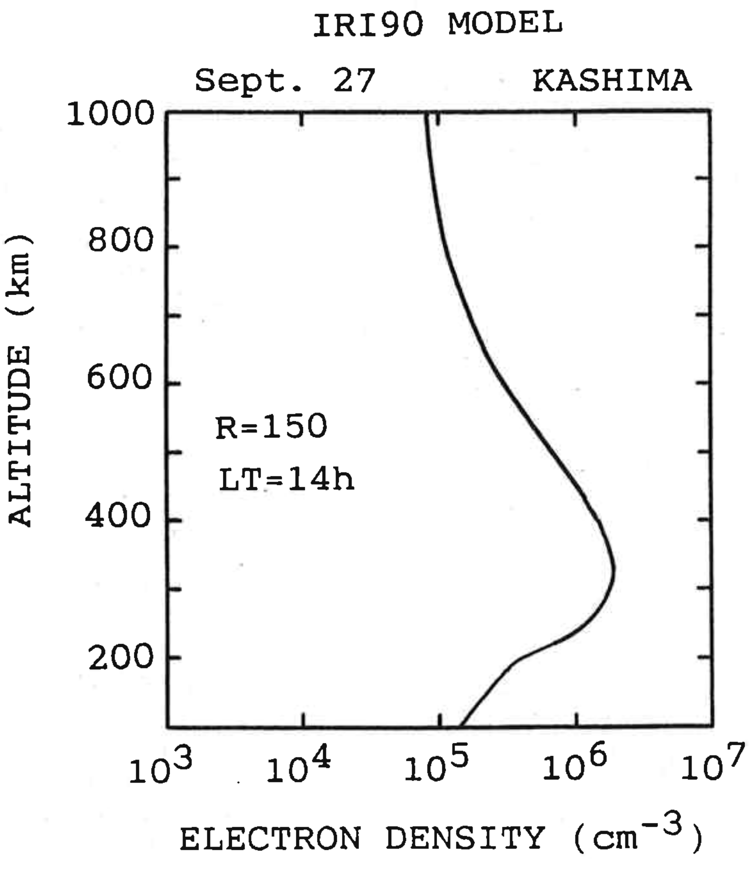


Fig.3 An example of electron density profile calculated by the international reference ionosphere model (IRI90) for Kashima station in local afternoon (local time, LT=14h) on Sept. 27 during high solar activity (sunspot number,R=150).

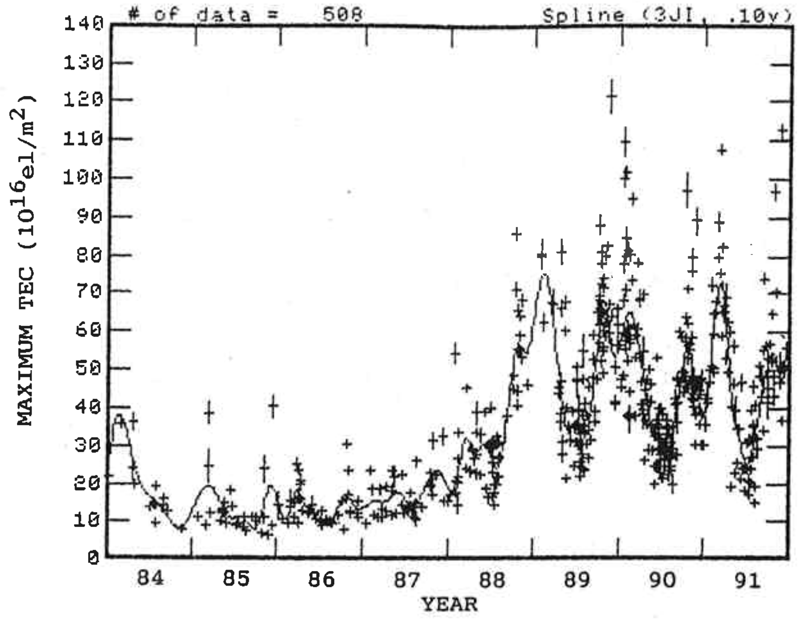


Fig.4 Maximum TECs in a day obtained for Mojave station for the period from 1984 to 1991 from the dual-band VLBI data. Spline fit of data is drawn in the figure with a solid line.

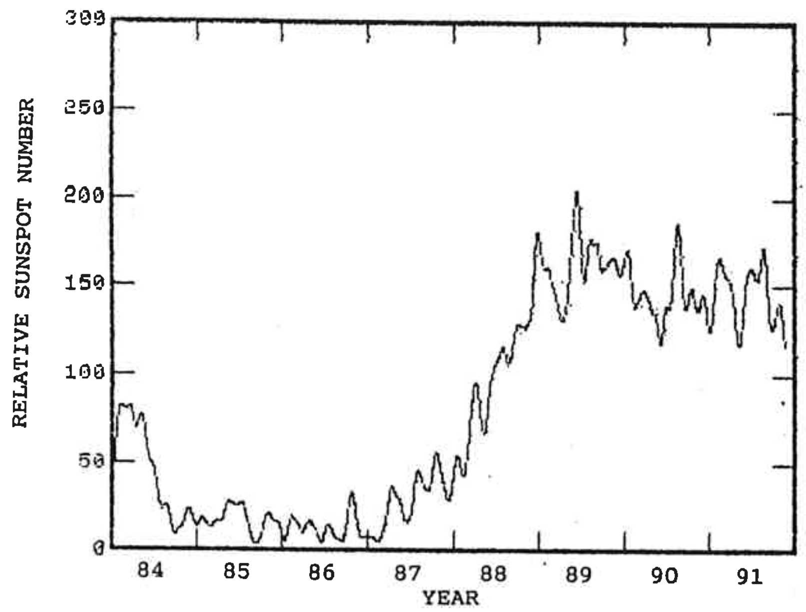


Fig.5 Smoothed plot of relative sunspot number.

Characteristics of maximum TEC in a day are investigated here in detail. Fig.4 shows an example of the maximum TECs obtained for Mojave station since 1984 to 1991. Smoothed relative sunspot number is depicted for the sake of comparison in Fig.5 for the same period. As well known, good correlation can be seen between sunspot number and the maximum TEC. Scatter plot of the maximum TECs and those calculated from the IRI90 model is shown in Fig.6 for Mojave. As shown in the figure, they are good correlated each other (correlation coefficient between them reaches about 0.8). Correlation coefficients ($r$) and two linear fitting parameters, inclination ($a$) and offset ($b$) are summarized in Table 1 for seven stations. They are also plotted in Fig.7 against the geomagnetic latitudes of the stations. Note that Fig. 7 reveals the existence of latitude dependence of parameters, especially $a$ and $b$. At middle latitude region($<40^o$), parameter $a$ keeps constant around 0.9, but reduces with increase of latitude in the high latitude region ($>40^o$). This suggests that the IRI model gives the overestimation of TEC in the high latitude area.

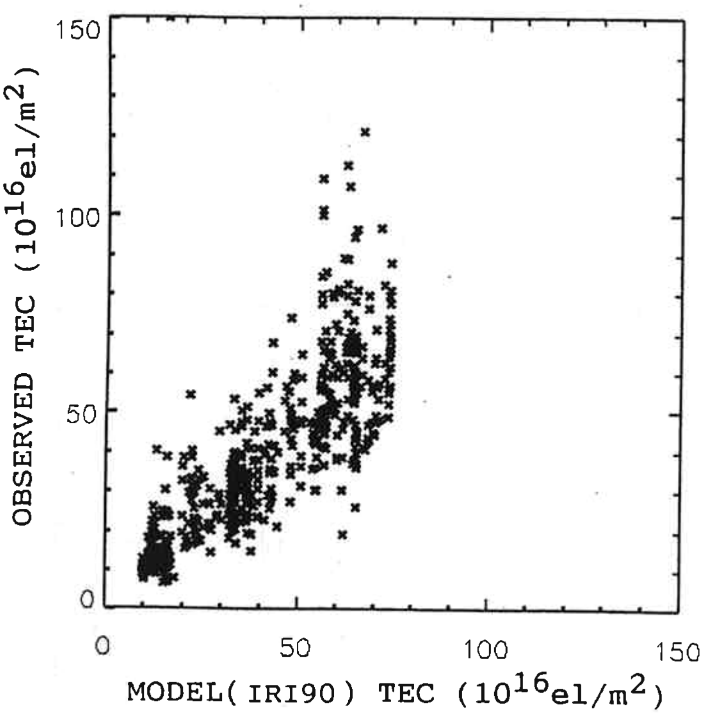


Fig.6 Comparison of observed maximum TECs and those calculated by the international reference ionosphere model for Mojave station for the period from 1984 to 1991. Ordinate is maximum TEC obtained by the dual-band VLBI data abscissa is that calculated by the IRI90 model. Note that good correlation can be seen (correlation coefficient is about 0.8).

Table 1. Results of Comparison

| STATION | GGEOMAG LATITUDE | # OF DATA | r | a | b |
|---|---|---|---|---|---|
| KAUAI | 21.4 | 207 | 0.74 | 0.95 | -4.6 |
| KASHIMA | 25.4 | 116 | 0.80 | 0.92 | -0.6 |
| RICHMOND | 36.9 | 592 | 0.86 | 1.07 | 0.1 |
| MOJAVE | 42.5 | 521 | 0.78 | 0.86 | 4.0 |
| WETTZELL | 49.2 | 627 | 0.86 | 0.67 | 2.9 |
| WESTFORD | 54.1 | 781 | 0.88 | 0.66 | 5.1 |
| GILCREEK | 64.6 | 469 | 0.67 | 0.48 | 7.6 |

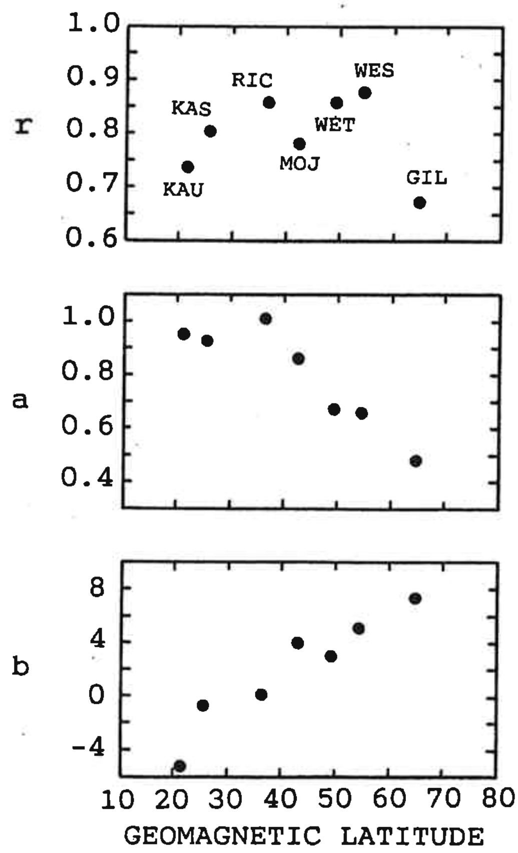


Fig.7 Results of model evaluations against geomagnetic latitude. Upper panel shows correlation coefficient ***r*** between maximum TECs observed and those calculated from the IRI90 model. Middle and lower panels show fitting parameters ***a*** and ***b*** which are slope and offset of line after linear fitting. When the IRI90 model overestimates the TEC, ***a*** takes the value less than unity. Note that ***a*** dcreases with increase of latitude in the high latitude area (>$40^{o}$).

## 3. Concluding Remarks

Quite two different aspects of the ionosphere regarding its relation to the VLBI measurements have been described. One is it as an obstacle for a precise geodetic measurement. The dual-band VLBI technique is used for the correction removing the ionospheric effects. An alternative way of ionospheric corrections using the TEC data measured by GPS receiver was proposed to realize a single-band VLBI for geodetic measurements. It is demonstrated that the new ionospheric correction works well with an accuracy of about 0.1ns for elevation angle range larger than 30 $^{o}$ in terms of X band delay.

The other aspect is the ionosphere measured by the dual-band VLBI as a by-product. From the dual-band VLBI data, we can obtain the TEC of each station participating in the VLBI session with the same accuracy. Owing to the CDP and the IRIS projects, the number of VLBI sessions available for TEC estimation is increasing year by year and the stations are now distributed world-widely from geomagnetic low latitude to high latitude. It is therefore very suitable for the investigation of the global ionosphere. From the point of this view, the characteristics of daily maximum TEC is investigated in contrast with the international reference ionosphere (IRI90). This comparative study indicates that the IRI model overestimates the TEC in the geomagnetic high latitude region (>40$^{o}$). Generally speaking, the IRI model is not adequate for the auroral region (around 60$^{o}$ geomagnetic latitude). So the approach demonstrated in this study might be useful for an improvement of the IRI model. In addition, it is possible to make a TEC model from the VLBI data instead. This will be a next step of the study.

**Acknowledgments**

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## References

Bilitza, D., International Reference Ionosphere 1990, National Space Science Data Center, NSSDC/WDC-A-R&S 90-20, Greenbelt Maryland, 1990.

Kondo,T. and S.Hama,"Estimation of total electron content using very long baseline interferometer", Proc.NIPR Symp. Upper Atmos.Phys.,3,pp.96-104,1990.

Kondo,T., Application of VLBI data to measurements of ionospheric total electron content, J.Commun.Res.Lab.,38,613-622,1991.

Kondo,T. and M.Imae, Precise ionospheric correction by using GPS signals for VLBI geodetic measurements, AGU geophysical monograph series, 1992 (in press).