

# A GPS-based method to model the plasma effects in VLBI observations

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**Abstract.** Global Positioning System (GPS) satellites broadcast at frequencies of 1,575.42 MHz (L1) and of 1,227.60 MHz (L2). The dispersive property of the ionosphere can be used to combine independent measurements at the two frequencies to estimate the total electron content (TEC) between a GPS receiver site and a broadcasting satellite. Such measurements, made at sites near to Very Long Baseline Interferometry (VLBI) sites, can be used to estimate the ionospheric contribution to VLBI observables. For our 1991.9 astrometric VLBI experiment in which we obtained group-delay observations in the 8.4 and 2.3 GHz bands simultaneously, we found that the GPS and VLBI determinations of the ionosphere delays agreed with root-mean-square differences below 0.15 ns for intercontinental baselines and 0.10 ns for continental ones. We also successfully applied the GPS-based procedure to reduce the ionospheric effect in phase delays used for high precision differenced astrometry at 8.4 GHz for this same experiment.

**Key words:** plasmas – atmospheric effects – methods: observational – techniques: interferometric – astrometry

## 1. Introduction

VLBI provides unprecedentedly accurate angular resolution through observations of celestial bodies with radio telescopes spread over the Earth's surface. Each observing station records data on magnetic tapes. The local-oscillator signals and the time-tagging of the data are governed by hydrogen-maser frequency standards. The tapes are processed in special-purpose correlators to determine the so-called VLBI observables: group and phase delays and phase-delay rates.

A main problem in determining the sky positions of celestial radio sources from these VLBI observables is the effect of the Earth's ionosphere on them. The use of GPS satellite data to remove this effect forms the thrust of this paper.

The ionosphere is characterized by its content of free electrons and ions. The F<sub>2</sub> layer of the ionosphere has the largest density of charged particles, with values up to  $3 \times 10^{12} \text{ m}^{-3}$ . The total electron content per square meter along a line of sight is the number of electrons in a column of one square meter cross section along the ray path:

$$\text{TEC} = \int_0^{h_0} N \cdot dh, \quad (1)$$

where  $N$  is the spatial density of electrons,  $h$  is the coordinate of propagation of the wave, and  $h_0$  corresponds to the effective end of the ionosphere. TEC is highly variable and depends on several factors, such as local time, geographical location, season, and solar activity. TEC can have values between 1 TECU (or TEC unit, defined as  $10^{16} \text{ m}^{-2}$ ) and  $10^3$  TECU. Epochs of greater solar activity cause higher values of the TEC.

The ionosphere affects the phase and group delays oppositely (to first order, see, e.g., Thompson et al. 1986):

$$\Delta\tau = \mp \frac{\kappa}{c\nu^2} \cdot \text{TEC}, \quad (2)$$

where  $\kappa \approx 40.3 \text{ m}^3 \text{ s}^{-2}$ ,  $c$  is the speed of light ( $\text{m} \cdot \text{s}^{-1}$ ), and  $\nu$  the frequency (Hz), and where we neglect magnetic field effects and assume  $\nu$  is large compared with the local plasma frequency (for an extreme case, the plasma frequency is of  $\sim 15$  MHz). The negative sign applies for phase delays and the positive sign for group delays. In standard astrometric VLBI experiments observations are made simultaneously in two well separated bands of frequencies in order to estimate the ionospheric effect. A nearly vacuum equivalent delay can be obtained from the following expression:

$$\tau_{\text{free}} = \frac{(\nu_1/\nu_2)^2 \tau_1 - \tau_2}{(\nu_1/\nu_2)^2 - 1}, \quad (3)$$

where  $\tau_i$  is the delay –either group or phase– at frequency  $\nu_i$  ( $i = 1, 2, \nu_1 > \nu_2$ ).

Thus, with dual frequency observations, the ionosphere effect can largely be removed from the VLBI data. Such removal can also be made for single-frequency observations via Eq. (2), if estimates of the TEC along the lines of sight of the radio telescopes are available from other observations.

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Guirado et al. (1995) showed that it is possible to estimate the ionospheric effect with accuracy useful for astrometric purposes from Faraday-rotation measurements. In this work, the authors used a “clipped” sinusoidal function to model the diurnal behavior of the TEC. In this model, the night component is constant and equal to the minimum TEC value, and the day component is expressed as the positive part of a sinusoid, with its maximum some hours after noon. Their observations were obtained in late 1985, a time of minimum solar activity.

In the method presented here we used GPS measurements that provide TEC values as a function of time. Such GPS-based TEC determinations were first successfully applied to geodetic VLBI by Sardón et al. (1992).

## 2. The Global Positioning System and the TEC

An introduction to the Global Positioning System (GPS) can be found in Hofmann-Wellenhof et al. (1997). A main use of the GPS system is to determine the position  $(x, y, z, t)$  of a GPS receiver on Earth’s surface. The system consists of a constellation of 24 satellites broadcasting electromagnetic signals in two narrow frequency bands, a set of monitoring ground sites, the Master Control Station, and GPS receivers. The 24 satellites orbit the Earth in near circular orbits with a 12 hr period, at a height of about 20,200 km, and an inclination of  $55^\circ$ . The spacecraft are in six orbital planes with four satellites nearly equally spaced along the orbit in each plane. At any moment, from any point on Earth, it is possible to detect signals simultaneously from 7 to 9 of these satellites. Each satellite broadcasts a block of data every 30 seconds, consisting of a description of its orbit and of GPS time, as well as a pseudo-random code every millisecond (coarse-acquisition C/A, for civilian use) and a precision code (P, 266 d period, for military use), usable to determine more accurately the position of the ground receiver.

The oscillators of the satellites generate a fundamental frequency  $\nu_0 = 10.23$  MHz, which is the P-code frequency. The C/A-code frequency is  $\nu_0/10$ . The GPS signal is emitted at two frequencies,  $154\nu_0$  and  $120\nu_0$  (L1 and L2, respectively, 1,575.42 MHz and 1,227.60 MHz, or  $\lambda\lambda 19$  and 24.4 cm). L2 carries only the P signal, and L1 both P and C/A signals.

### 2.1. The GPS observables

The main GPS observable is  $dT$ , the time of transit of the signal from the satellite to the ground receiver. The value of  $dT$  can be determined, in effect, by comparing the time of broadcasting of the codes P or C/A with the time of receipt of these codes. An observable that corresponds to  $dT$  can be obtained by cross correlation of the signal received from the satellite at each band with a reference signal generated at the receiver and “tied” to GPS time. In this case,  $dT = \phi/2\pi\nu$ , where  $\phi$  is the total phase change of the signal during propagation from satellite to receiver and  $\nu$  is the center frequency of this transmitted signal. This observable is the phase delay of the carrier signal.

The GPS observable is affected by the following: the ionosphere, the troposphere,  $2\pi$  phase ambiguities (equivalent to

multiples of 634.75 ps and 814.60 ps, respectively, for L1 and L2), multipath (e.g., from signals that are reflected or scattered into the receiver antennas from objects nearby to it), different effective location of receivers for L1 and L2, instrumental delays (different for L1 and L2), degraded coding of the signals, and clock errors. The contributions to the observables of the largest of these effects can be sharply reduced by application of suitable techniques (see, e.g., Blewitt 1990).

### 2.2. Obtaining the TEC from GPS data

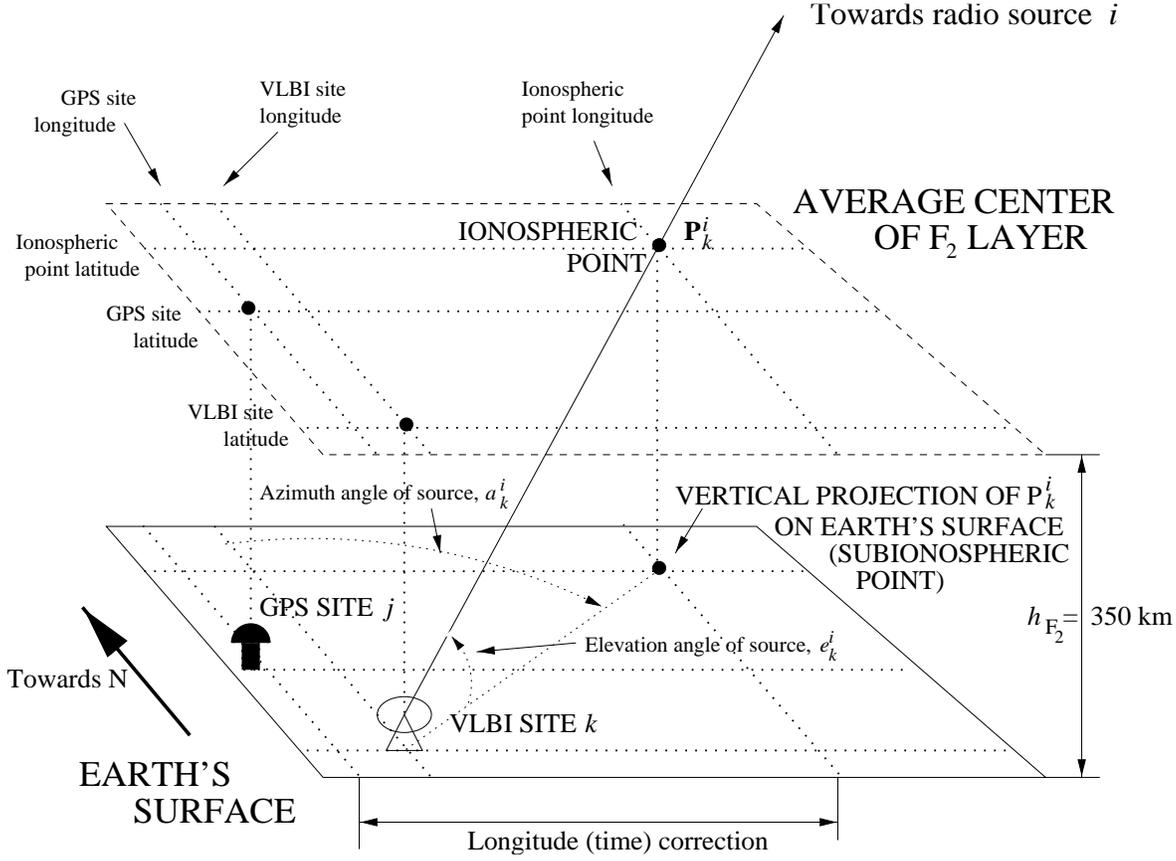
The GPS observable can be modeled as a function of distance from satellite to receiver, ionospheric delays, tropospheric delays, clock errors, and instrumental phase- and group-delay biases (Sardón et al. 1994). The ionospheric term can be estimated by a combination of the L1 and L2 observables. We can denote the TEC for any observation direction as  $I_k^i(t)$ . This TEC is defined along the line of sight from the radio telescope  $k$  to the radio source  $i$  and can be expressed approximately as a function  $\mathcal{V}$  (vertical value of TEC) of time  $t$  and the intersection point  $P_k^i$  (“ionospheric point”) of the line of sight from  $k$  to  $i$  with the (average) F<sub>2</sub> layer of the ionosphere (at an altitude of  $h_{F_2} = 350$  km), times the obliquity or slant function  $S(e_k^i)$ , defined as the secant of the zenith angle at the ionospheric point (see below for geometry clarification), which is a function of the elevation angle  $e_k^i$  of the observation:

$$I_k^i(t) = S(e_k^i) \cdot \mathcal{V}(P_k^i, t). \quad (4)$$

The positions of the involved sites and the ionospheric points can be expressed in a geocentric coordinate system  $(X, Y, Z)$  or in a geocentric-solar one  $(\Psi, \chi, Z')$  with the  $Z'$  axis directed toward the Sun from the Earth center,  $\Psi$  the angle in the  $XY$ -plane (measured counterclockwise from  $X$ ) and  $\chi$  the angle with apex at the Earth’s center, measured from the direction to the Sun ( $Z'$ ) to the direction to  $P_j^i$ . This latter coordinate system is useful since the ionosphere is roughly time-independent in this reference frame. Following Sardón et al. (1994), we replace  $\mathcal{V}$  for a GPS site  $j$  and satellites  $l$  by its locally linear approximation in  $P_j^l$  (ionospheric point towards satellite  $l$ ) using the  $(\Psi, \chi, Z')$ -coordinate system:

$$I_j^l(t) = S(e_j^l) \cdot [A_j(t) + B_j(t)d\Psi_j^l(t) + C_j(t)d\chi_j^l] + K^l + K_j. \quad (5)$$

Here, the coefficients for each site are  $A$  (0<sup>th</sup> order, vertical),  $B$  (1<sup>st</sup> order,  $\Psi$ -direction),  $C$  (1<sup>st</sup> order,  $\chi$ -direction). We have also introduced the instrumental GPS satellite  $K^l$  and receiver  $K_j$  biases.  $A_j(t)$  is the vertical TEC at site  $j$ ,  $d\Psi_j^l(t) = \Psi_j^l - \Psi_j$ , and  $d\chi_j^l = \chi_j^l - \chi_j$  are the coordinates  $\Psi$  and  $\chi$  of the ionospheric point of the line of sight from  $j$  towards the satellite  $l$  minus the corresponding coordinates of the GPS site  $j$ . The coefficients  $A, B, C$ , can be determined, and the  $K$ -biases largely removed, using a Kalman filtering method (Herring et al. 1990) with the data from different satellites  $l$  (about 8 at a time) to obtain an estimate of the TEC from GPS data. The  $K$  biases can be due to such effects as errors in the estimation of phase



**Fig. 1.** Geometry used to estimate TEC from GPS measurements (see text). The vertical lines here are radial (from the Earth's center) and the tangent planes drawn are approximations to the surface of spheres (Earth and F<sub>2</sub> layer of ionosphere) having, e.g., the VLBI site and its ionospheric point as points of tangency.

ambiguities and multipath (see Sardón et al. 1994). In sum, we produce estimates of the total electron content of the ionosphere using data from a network of GPS stations and a multiplicity of satellites.

### 3. Vertical TEC from GPS and TEC for VLBI

Here we describe the formulas we used to estimate the TEC along the paths of a VLBI observation from the values of the vertical TEC (evaluated by the method described in Sect. 2.2) at a GPS site near each one of the VLBI sites.

Consider a GPS site  $j$  at latitude  $\zeta_j$  and longitude  $\lambda_j$ , and a VLBI site  $k$  at position  $(\zeta_k, \lambda_k)$  (see Fig. 1). The coordinates of  $P_k^i$ , denoted by  $(\zeta_{P_k^i}, \lambda_{P_k^i})$  at the epoch the radio source is at elevation  $e_k^i$  and azimuth  $a_k^i$ , are (Klobuchar 1987):

$$\zeta_{P_k^i} = \arcsin(\sin \zeta_k \cos \mathcal{E}_j^i + \cos \zeta_k \sin \mathcal{E}_j^i \cos a_j^i) \quad (6)$$

$$\lambda_{P_k^i} = \lambda_k + \arcsin\left(\frac{\sin \mathcal{E}_j^i \sin a_j^i}{\cos \zeta_{P_k^i}}\right), \quad (7)$$

where  $(-\pi/2 \leq \zeta_k \leq \pi/2)$  and the arcsin-function in  $\lambda$  holds for values in the interval  $(-\pi/2, \pi/2)$ , appropriate for Eq. (7) since GPS and VLBI sites are nearly collocated.  $\mathcal{E}_k^i$  is the angle, measured from the center of the Earth between the

line to site  $k$  and the line to the ionospheric point for radio source  $i$ :  $\mathcal{E}_k^i = \pi/2 - e_k^i - \arcsin(\Xi \cos e_k^i)$  (see Fig. 2, where  $\Xi = R_\oplus / (R_\oplus + h_{F_2})$ ,  $R_\oplus$  is the Earth's radius, and  $\Xi \approx 0.948$  for  $h_{F_2} = 350$  km). The local time at the ionospheric point is  $t = (\lambda_{P_k^i}/15) + \text{UT hr}$  ( $\lambda$  in degrees, with  $\lambda$  positive to the East).

We assume that the vertical TEC  $A_{P_k^i}(t)$  at the ionospheric point is given in terms of  $A_j(t)$  by:

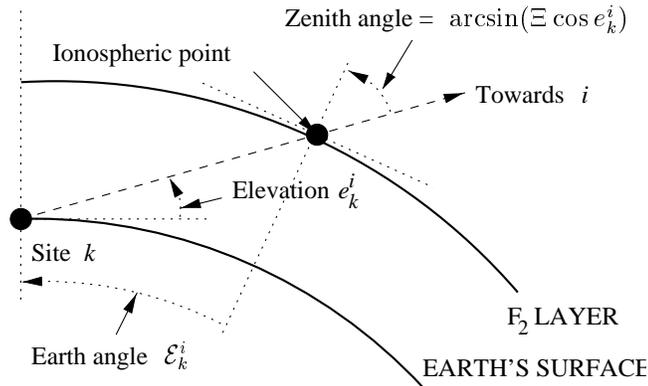
$$A_{P_k^i}(t) = A_j\left(t + \frac{\lambda_{P_k^i} - \lambda_j}{15}\right). \quad (8)$$

This relation effects a longitude correction but ignores any latitude dependence of the TEC values. This approach is reasonable for mid-latitude stations and sources at high declination since GPS sites can be collocated with VLBI sites, or at least placed relatively near to them, and since TEC changes more rapidly with longitude than with latitude.

The slant factor was defined above as the secant of the zenith angle, which is  $\arcsin(\Xi \cos e_k^i)$  (see Fig. 2, and Klobuchar 1987). Thus, the TEC at the ionospheric point  $P_k^i$ , mapped by the slant factor (Eq. 4) gives

$$I_k^i(t) = \sec\{\arcsin(\Xi \cos e_k^i)\} \cdot A_{P_k^i}(t), \quad (9)$$

which, with Eq. (2) yields our estimate of the ionospheric delays at the indicated VLBI site. The overall ionospheric effect on a



**Fig. 2.** Geometry of the obliquity or slant factor, which is the secant of the zenith angle, defined by the elevation  $e_k^i$  (see text for definition of  $\Xi$ ). Curvatures of the Earth's surface and the ionosphere  $F_2$  layer are exaggerated for clarity.

VLBI observable is a simple linear combination of the effects from each of the two sites involved in the observation.

#### 4. A case to test the method:

##### VLBI observations of the Draco triangle

Progress in high precision phase-delay difference astrometry has been made by Ros et al. (1999) through VLBI observations of triangle formed by the radio sources BL 1803+784, QSO 1928+738 and BL 2007+777, in the Northern constellation of Draco (the Dragon). The observations were made simultaneously at the frequencies of 2.3 and 8.4 GHz at epoch 1991.89 with an intercontinental interferometric array. The angular separations among these radio sources were determined with submilliarcsecond accuracy from a weighted-least-squares analysis of the differenced and undifferenced phase delays. The modeling of these astrometric VLBI observations was sufficiently accurate to estimate reliably the “ $2\pi$  ambiguities” in the differenced phase delays for source separations of almost  $7^\circ$  on the sky. For such angular distances, this accurate “phase connection” at 8.4 GHz, yielding the phase delays with standard errors well within one phase cycle over the entire session of observations, was demonstrated at an epoch of solar maximum. As in earlier works (e.g., Guirado et al. 1995, Lara et al. 1996), after phase connection the effects of the extended structure of the radio sources were largely removed from the phase-delay observables. The effects of the ionosphere were also mostly removed, via the GPS-based method described in this paper.

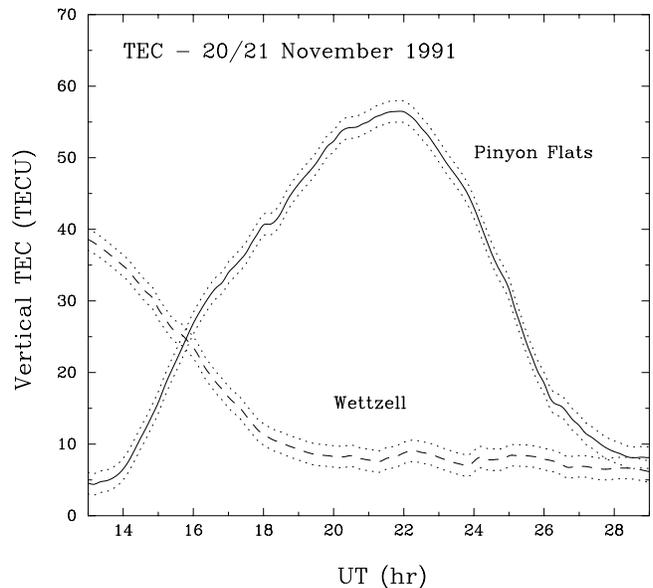
In 1991 the number of available GPS sites was small, and only data from Goldstone and Pinyon Flats in the US, and from Herstmonceux and Wettzell in Europe (see Table 1 for details) were available to be used for our experiment. GPS data from the two US sites were used for the VLBI sites at Fort Davis (TX), Pie Town (NM), Kitt Peak (AZ), and Los Alamos (NM) to estimate the TEC for observations at these sites. Similarly, GPS data from both European sites were used for Effelsberg (Germany). The VLBI observations were carried out from 14 hr UT on 20 November to 4 hr UT on 21 November 1991. In Fig. 3 we show

**Table 1.** Positions of the GPS sites and the VLBI sites (Ros et al. 1999) and maximum and minimum values of the vertical TEC value on 20/21 November 1991 (see text for definitions of notation).

GPS site	$\zeta_j$	$\lambda_j$	$A_j^{\min}$ [TECU]	$A_j^{\max}$ [TECU]	VLBI site	$\zeta_k$	$\lambda_k$
DS10 <sup>1</sup>	35.2 N	116.9 W	5	57	FD <sup>a</sup>	30.6 N	103.9 W
PIN1 <sup>2</sup>	33.6 N	116.5 W	5	57	PT <sup>b</sup>	34.3 N	108.1 W
					KP <sup>c</sup>	32.0 N	111.6 W
					LA <sup>d</sup>	35.8 N	106.2 W
HERS <sup>3</sup>	50.9 N	0.3 E	8	38	EB <sup>e</sup>	50.3 N	6.8 E
WTZ1 <sup>4</sup>	49.1 N	12.8 E	8	39			

<sup>1</sup> Goldstone Deep Space Tracking Station, NASA, CA, US; <sup>2</sup> Pinyon Flats Observatory, SIO, UCSD, CA, US; <sup>3</sup> Herstmonceux, East Sussex, England; <sup>4</sup> Kötzing, IFAG, BKG, Bavaria, Germany.

<sup>a</sup> Fort Davis, VLBA, NRAO, TX, US; <sup>b</sup> Pie Town, VLBA, NRAO, NM, US; <sup>c</sup> Kitt Peak, VLBA, NRAO, AZ, US; <sup>d</sup> Los Alamos, VLBA, NRAO, NM, US; <sup>e</sup> Effelsberg, MPIfR, North-Rhine-Westphalia, Germany.



**Fig. 3.** Values of the vertical TEC at the GPS sites of Pinyon Flats (CA, US) and Wettzell (Germany) (Ros et al. 1999). These values were used to compute the TECs at nearby VLBI sites. We assumed an error of 1.5 TECU (represented by the dotted lines), much larger than the statistical standard errors.

the corresponding vertical TEC values for one of the GPS sites on each continent. We see the dusk and night part of the data for Wettzell, and the daylight data for Pinyon Flats.

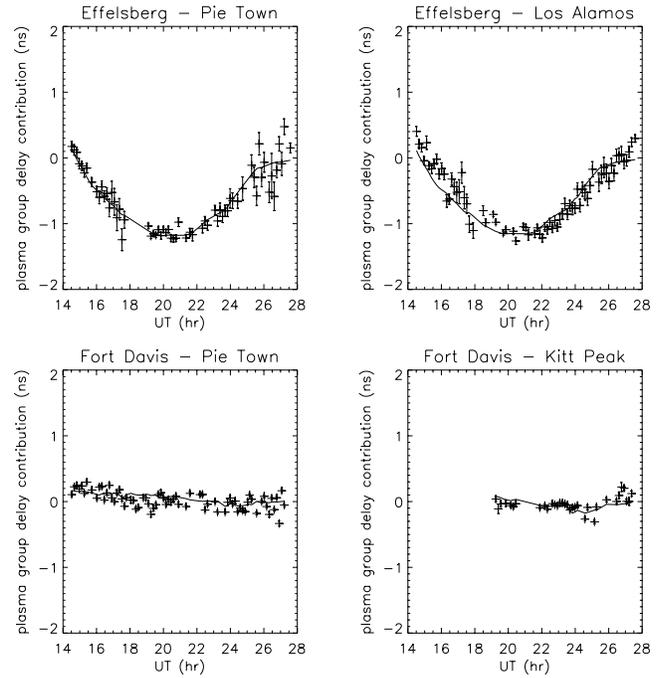
From the GPS-based estimates of the TEC along the lines of sight for each VLBI site, we calculated the ionospheric contribution for each baseline and epoch of observation. These ionospheric contributions were removed from the VLBI observables. For the phase delays, these contributions ranged in magnitude from 0 to 1.2 ns at 8.4 GHz for intercontinental baselines, and were less than 0.1 ns for continental baselines. The intercontinental baseline lengths range from  $\sim 7800$  to  $\sim 8300$  km, and the differences in local time are  $\sim 7.5$  hr (see Fig. 3). Since the iono-

spheric effect is the combination of effects for both antennas, the ionospheric delay is quite important for our intercontinental baselines. By contrast our US-continental baseline lengths range from  $\sim 200$  to  $\sim 750$  km which corresponds at most to about 30 minutes difference in local time and a much smaller ionospheric effect on the VLBI observables.

Eq. (3) provides the usual way to largely remove the effect of the ionosphere on dual-band VLBI observations. The phase delays from our 2.3 GHz observations could not be freed from  $2\pi$  ambiguities due to the large scatter in these data. However, unambiguous but less precise group delays were available at both 2.3 and 8.4 GHz. The ionospheric contributions were estimated from these group-delay data. In Fig. 4 we show the comparison of GPS-based and dual-band VLBI-based ionospheric delay estimates at 8.4 GHz. We show four of the ten available baselines as representative examples: two intercontinental and two continental-US ones. Apart from the larger dispersion in the group-delay than in the GPS-based data, this comparison provides a good independent confirmation of the reliability of the GPS-based method for the correction of VLBI data. The error bars for the group delays shown in the figure are the appropriate combination of the statistical standard errors for the data at these frequencies (see Eq. 3). The statistical standard errors for the GPS estimates are each about 0.2 TECU. We assume a much larger standard error  $-1.5$  TECU– to try to account for possible inaccuracies not estimated with the Kalman filtering, such as incorrect values for  $h_{F_2}$ , the consequent changes in the mapping function and in the eventual position of the ionospheric point, and other unmodeled effects. Thus, we infer a corresponding contribution of  $\sim 30$  ps to the standard errors of the phase delays at 8.4 GHz. For the data presented in Fig. 4, the root-mean-square of the differences between the results from the two methods are below 0.15 ns for intercontinental baselines and 0.10 ns for continental ones.

## 5. Conclusions

Assuming that the ionosphere can be modeled usefully as a thin shell surrounding the Earth at a height of 350 km, we estimate the TEC for the line of sight from the GPS site to the satellite using ground reception of GPS signals and knowledge of the orbital parameters of the GPS satellites. Having a GPS site near a VLBI site, we can reliably “transfer” this estimate to the TEC for the line of sight from the radio telescope to the radio source. These TEC values allow us to correct the VLBI observables for the effects of the ionosphere for any frequency. We made such corrections for our phase-delay data at 8.4 GHz (Ros et al. 1999) for an epoch at which there was a paucity of relevant GPS data. The estimates of the ionospheric delays provided by the VLBI measurements of group delay at 2.3 and 8.4 GHz differ from the corresponding delays obtained from GPS data to within root-mean-square values below 0.15 ns for intercontinental baselines and 0.10 ns for continental ones. Thus, we have shown, in particular, that the GPS determination of TEC can be successfully used in the astrometric analysis of VLBI observations.



**Fig. 4.** Comparison between the ionospheric delays at 8.4 GHz estimated by the combination of group delays at 8.4 and 2.3 GHz from the VLBI observations of Ros et al. (1999) (points with error bars) and the corresponding ionospheric delays estimated by the GPS-based TEC determination reported here (solid line). Data from four representative baselines of a total of ten from the VLBI experiment are shown here. Root-mean-square values for the differences are, respectively, of 0.11, 0.15, for the upper panels and of 0.10, 0.08 ns for the lower panels.

The density of the network of GPS sites has increased dramatically since 1991 and the accuracy of the TEC deduced from GPS data has improved significantly. Given such progress, the approximations used in this paper are no longer necessary. Now GPS estimates for the vertical TEC are available from virtually every land location all of the time and thus for every VLBI observation.

The advantages of GPS compared with geostationary beacons which used Faraday rotation to determine TECs are notable: global land coverage for GPS is available from geodetic networks (e.g., the International GPS Geodynamics Service); the TEC estimates do not depend on assumptions about the Earth’s magnetic field; L1 and L2 GPS data are available over the internet in standard formats (e.g., RINEX: Receiver INdependent EXchange). We also note that the ionosphere cannot always be represented by a thin shell model with good accuracy; moreover, more accurate models can be devised and suitably parameterized given the tomography-like sampling of the ionosphere provided by the GPS. The biases in the GPS observables have to be properly corrected in the estimates of TECs. Davies & Hartmann (1997) set an upper limit of 3 TECU for the present agreement of GPS-based TEC with the results from other methods, but only of few 0.01 TECU for the relative errors of TEC estimates over the course of some hours for any given site. The latter represents relative changes of delay at 8.4 GHz of 0.2 ps,

nearly two orders of magnitude smaller than the delay equivalent of a  $2\pi$  phase ambiguity. With such accuracies and the present network of GPS sites, the removal of most of the effect of the ionosphere from VLBI observations should not be difficult, although much of the smaller-scale ionospheric activity cannot be adequately sampled by GPS. From dual-band difference VLBI astrometry and GPS data, the optical depth of the emission in radio sources can be better studied by comparing brightness distributions obtained independently at each frequency band with respect to the same coordinate system. In sum, the introduction of GPS techniques should greatly improve the scientific results obtained from VLBI observations.

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