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Comparison of Ionospheric Activity Derived from GPS and Different VLBI Networks

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Abstract

GPS is currently the space geodetic technique most widely used for ionospheric studies, and provides broad coverage with high spatial and temporal resolution. Due to the nature of the dual frequency observations, VLBI is also capable of sensing the total electron content (TEC) of the ionosphere. We compare the ionospheric activity derived from different VLBI networks with the global GPS results from the Center of Orbit Determination in Europe and find that the difference between the techniques is on the order of 10 TEC units.

1. Introduction

The ionosphere is the region surrounding Earth that consists of particles charged by radiation processes, e.g. the ultraviolet radiation from the Sun. The resulting ions are subject to an electrodynamic drift over the magnetic equator, and their subsequent distribution along magnetic field lines results in an equatorial anomaly that is characterized by two crests around 30° geomagnetic latitude and a trough in between. Due to the strong dependency on solar activity, the ionosphere exhibits significant increase during local daytime.

Generally, an electromagnetic wave propagating through a medium is governed by the refractive index, n, of the medium. For the radio frequencies used by space geodetic techniques like VLBI and GPS, the ionosphere acts as a dispersive medium. With dispersiveness it is understood that the refractive index is frequency dependent, a frequency dependence that also can be utilized to study the ionosphere. The phase refractive index, n_{ph}, of a dispersive medium can be approximated with the series

$$n_{ph} = 1 + \frac{c_2}{f^2} + \frac{c_3}{f^3} + \frac{c_4}{f^4} + \ldots$$

where c_2, c_3 and c_4 are coefficients that depend on the electron density, N_e, along the signal path and not on the frequency. Higher order expansions are usually cut off and with an estimate of $c_2 = -40.3 N_e$ [Hz^2], the phase refractive index becomes

$$n_{ph} = 1 - \frac{40.3}{f^2}$$

The propagating signals are affected by the total electron content (TEC) during their way through the ionosphere. TEC is the integral of the electron densities along the signal path, s,

$$\mathrm{TEC} = \int N_e ds$$

and using the above, the ionospheric phase refraction Δ_{ph}^{Iono} results:

$$\Delta_{ph}^{Iono} = -\frac{40.3}{f^2}\mathrm{TEC}$$

Usually, TEC is measured in TEC units (TECU) corresponding to 10^{16} electrons. Although the ionosphere ranges from roughly 75 km to 1000 km height, a thin shell approximation is sufficient for most applications. More thorough derivations and descriptions than the above can be found in e.g. [1]. Utilizing the dual-frequency observations that are used in both VLBI and GPS, information about the TEC in the ionosphere can be derived [2], [3].

Comparison of differential TEC values derived from global GPS-based TEC maps and VLBI observations show a high degree of agreement between the two techniques [4]. Correlation on the level of 0.6–0.9 was achieved on short and intercontinental baselines.

In another comparison between VLBI and GPS [5], it was shown that the two techniques can yield similar TEC values at a VLBI site. Although using the same fundamental equations, the TEC solutions at each site were determined in different ways for the two techniques. For VLBI, the solutions were obtained from one point (the station) and mapped to the zenith, whereas for GPS, the solutions were based on a global spherical harmonics expansion of several sites.

In this study, we use the full set of ionospheric data obtained by VLBI at all observing sites for an experiment and compare these to a global set of GPS TEC observations. The comparison is then made for the region of a global spherical harmonics expansion confined by the outer limits of the VLBI observations.

2. Ionospheric Information Derived from VLBI

Differential ionospheric VLBI delays were used to estimate coefficients of the spherical harmonic expansion of the global field of vertical TEC. A simple single-shell model for the ionosphere with an ionospheric height of 450 km was applied. The point where the signal propagates through the infinitesimally thin modelled ionospheric shell is termed the ionospheric pierce point (IPP). Figures 1a shows an example of the IPPs for the T2002 experiment, observed February 12, 2002. The geographic longitudes λ_{pp} of the IPPs were then rotated to a sun-fixed longitude $\lambda_{\odot}$. With $\lambda_{pp} = 0°$ at 12 UT in the rotating earth-fixed frame corresponding to $\lambda_{\odot} = 0°$ in the sun-fixed frame, the generalized

$$\lambda_{\odot} = \lambda_{pp} + \mathrm{T} \cdot \omega_e \pm \pi$$

appears, where T is time (UT) and ω_e is the angular velocity of the earth. By rotating the earth-fixed observations of the experiment, an essential 360° longitudinal spread was obtained, Figure 1b. The importance of the VLBI network geometry for the spatial distribution of the IPPs and thus the sampling of the ionosphere is obvious.

Weak constraints were used to stabilize the least-squares estimation process to determine the coefficients of the spherical harmonic approach to degree and order 6. The estimated coefficients were used to create global VLBI TEC maps.

3. Ionospheric Information Derived from GPS

The international GPS service (IGS) homepage currently features daily ionospheric global solutions from five different analysis centers world-wide [6]. For our comparisons, we chose the

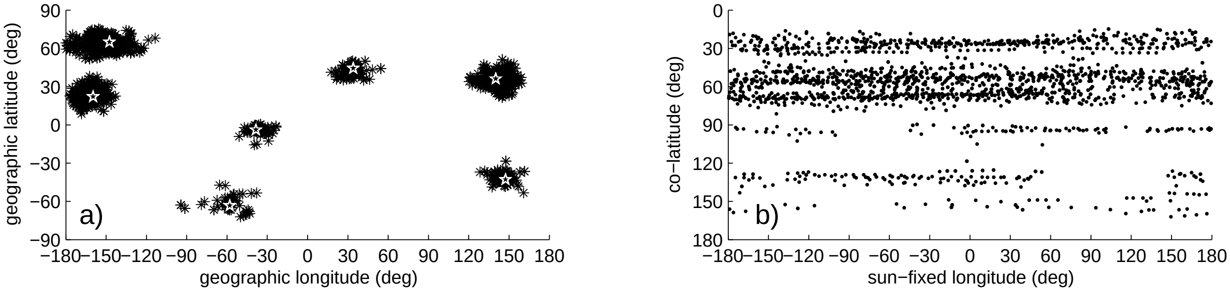

Figure 1. VLBI ionospheric pierce points during T2.002 in a) earth-fixed and b) sun-fixed reference frame. The VLBI stations are indicated by white pentagrams in a).

solutions by the Center of Orbit Determination in Europe (CODE) at the University of Berne [7]. CODE uses observations from around 150 sites to obtain bi-hourly solutions of the total vertical electron content and each 24-hour period is represented by thirteen[1] maps with a resolution of 2.5° in latitude and 5° in longitude. The IONEX maps generated at CODE are obtained using a modified single-layer model mapping function and are based on a spherical harmonics expansion of the observations up to degree and order 15. The maps correspond to the results for the middle day of a 3-day combination analysis in order to provide a set with consistent accuracy throughout. Further information on IONEX files and how they are generated is available at the CODE homepage. We used the bi-hourly IONEX data to create maps of the average TEC content during 24 hours, corresponding to the simultaneously observed VLBI experiments, see Figure 2.

4. Comparison of GPS and VLBI Results

To make the comparison between GPS and VLBI data feasible, we chose the following approach. The geographic coordinates (ϕ_{dp}, λ_{dp}) of the ionospheric pierce points (VLBI) and IONEX grid nodes (GPS), henceforth referred to as data points, were rotated into solar-geomagnetic coordinates in two steps. Following [8], the geomagnetic latitudes ϕ_m of the data points were calculated using

$$\sin\phi_m = \sin\phi_{dp}\sin\phi_p + \cos\phi_{dp}\cos\phi_p\cos(\lambda_{dp} - \lambda_p)$$

approximating the Boreal pole at $\phi_p = 78.7°$N and $\lambda_p = 290.1°$E. The IONEX data and the VLBI observations were rotated to a sun-fixed longitude as described in the previous section. GPS data were averaged over the 24-hour period before being compared to the VLBI maps, in order to make the data sets represent equal periods in time. The data points thus observed at non-uniformly spaced solar-geomagnetic coordinates were then projected onto a uniform grid (2.5°lat×5°lon) of solar-geomagnetic coordinates in order to make the comparison efficient. To avoid extrapolation of the observed data, the comparison has been confined to a region bound by the geomagnetic northern- and southernmost IPPs.

Figure 2 shows GPS and VLBI derived TEC maps for the dates of eight VLBI experiments in 2002 with different network geometries. To derive some statistics of VLBI and GPS differences, we followed the scheme described above also for the CONT02 campaign, which observed continuously for two weeks in October 2002. Figure 3 shows the differences for all experiments during

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[1] Until 2002 day 306, twelve maps corresponding to UT 1,3,...,23 were generated (valid for this study).

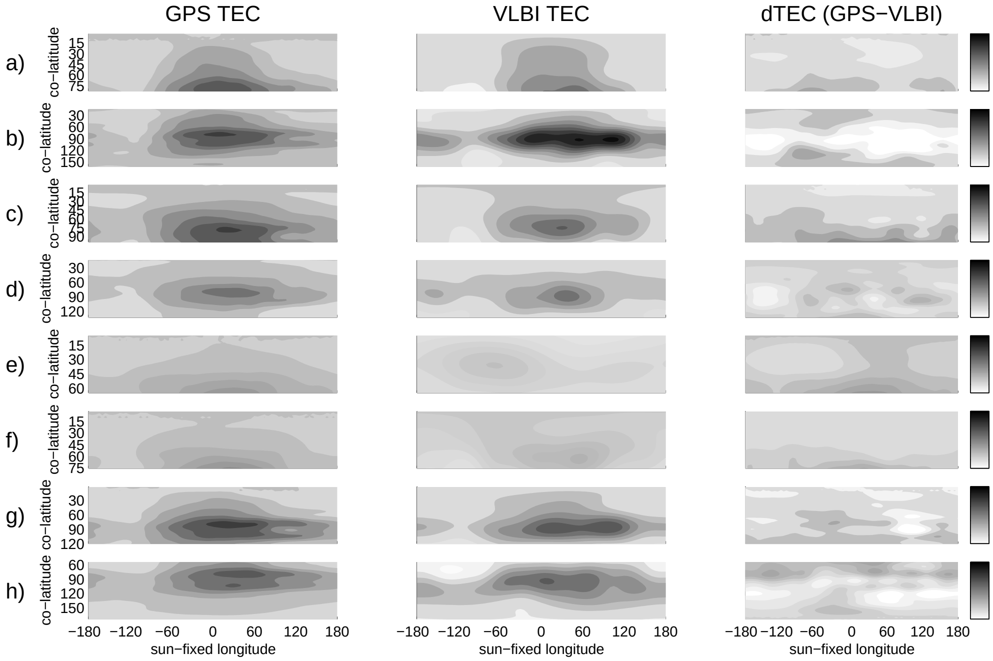

Figure 2. Solar-magnetic TEC maps from GPS and VLBI together with the difference between the two techniques for: a) RDV31, b) T2002, c) R4015, d) R1020, e) EURO64, f) R&D-7, g) CONT02.02 h) OHIG20. All values are given in TECU.

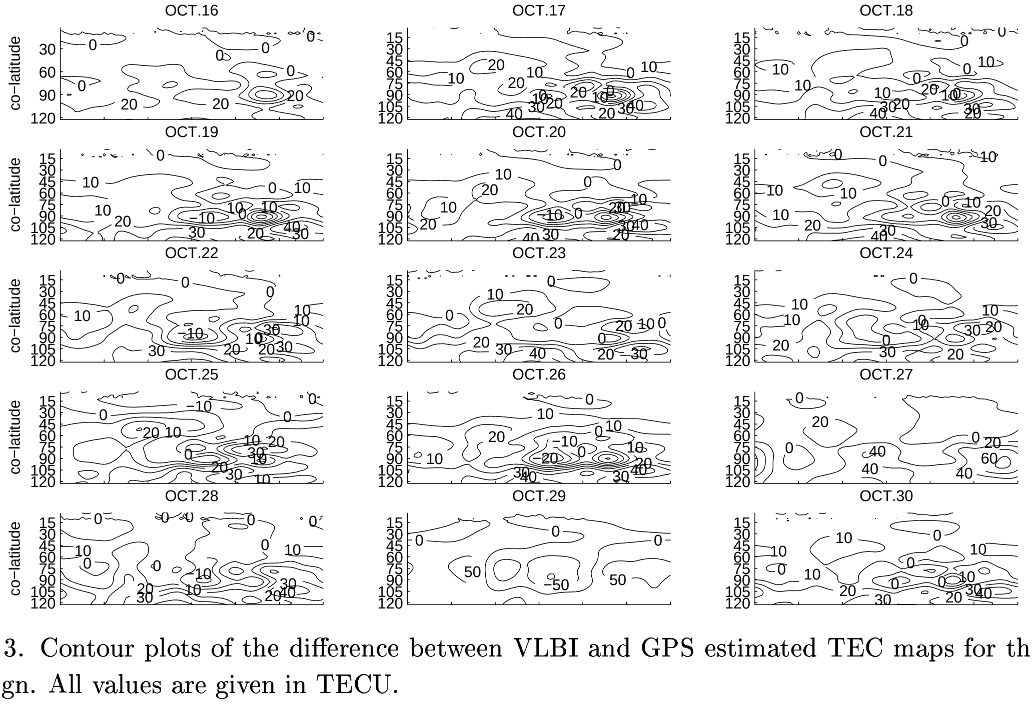

Figure 3. Contour plots of the difference between VLBI and GPS estimated TEC maps for the CONT02 campaign. All values are given in TECU.

the CONT02 campaign. Mean TEC differences and their standard deviations for the CONT02 campaign are given in Table 1.

Table 1. Mean TEC differences in TECU between GPS and VLBI for CONT02.

Day	dTEC(GPS-VLBI)	Day	dTEC(GPS-VLBI)	Day	dTEC(GPS-VLBI)
Oct16	9.904 ± 13.310	Oct21	8.344 ± 11.110	Oct26	9.658 ± 13.043
Oct17	12.541 ± 11.748	Oct22	9.856 ± 11.793	Oct27	15.335 ± 19.893
Oct18	11.531 ± 10.882	Oct23	10.377 ± 11.268	Oct28	7.798 ± 11.713
Oct19	9.307 ± 11.185	Oct24	11.052 ± 10.162	Oct29	8.368 ± 33.395
Oct20	11.000 ± 12.156	Oct25	8.151 ± 12.778	Oct30	10.165 ± 9.706

5. Conclusions and Outlook

Both GPS and VLBI allow derivation of the total electron content in the ionosphere. An important restriction for ionospheric studies with VLBI is the sparse spatial sampling of the ionosphere provided by current VLBI networks. The analyzed examples show similarities, but also significant discrepancies between the two techniques. The agreement of TEC maps derived from the two techniques is of the order 10 TECU. Current VLBI networks with 8–20 participating stations do not allow as highly and well distributed samplings of the ionosphere as GPS does. It also appears that regional observations (e.g. EURO experiments) are less suitable for this type of analysis. Derivation of accurate global TEC maps with high resolution from VLBI data is thus a challenging task and requires further investigations. The combined use of the two complementary techniques for ionospheric studies might be a meaningful approach.

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