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Determination of Ionospheric Parameters by Geodetic VLBI

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Abstract

In geodetic VLBI the observations are performed at two frequencies (2.3 and 8.4 GHz) in order to determine ionospheric delay corrections. This also provides information about the total electron content (TEC) of the ionosphere from VLBI observables. Various VLBI sessions are used to determine TEC differences. The results are compared with TEC values obtained from GPS within IGS (IONEX). A very good agreement can be observed, in particular for baselines longer than 2000 km. By using external information for absolute calibration it is possible to calculate the unknown offset per baseline and to generate regional maps of TEC values, e.g. over Europe. Animated maps that represent the time dependency of the data are also produced and compared with GPS solutions.

1. Theory

The refraction of electromagnetic waves by the ionosphere was described e.g. by Brunini (1997) [1], Hartmann and Leitinger (1984) [2], Lohmar (1985) [3], and Schaer (1999) [4]. Adaption to VLBI yields for the slant total electron contents $STEC_i$ observed at the two stations $i = 1, 2$

$$\underbrace{STEC_2 - STEC_1}_{\Delta STEC} = \frac{\tau_X - \tau_S}{40.28\left(\dfrac{1}{f_X^2} - \dfrac{1}{f_S^2}\right)} + offset \tag{1}$$

The left side of equation (1) can be derived from group delay measurements τ_X and τ_S in X- and S-band if the baseline-dependent offset is known. The equation is only valid for the effective ionospheric frequencies f_x and f_s contained in the denominator on the right side. One total electron content unit (TECU) equals 10^{16} electrons in a volume with a cross section of 1 m^2 that reaches from the antenna along the ray path. STEC values observed at zenith distance z_i are transformed into vertical TEC (VTEC) values at station i by

$$VTEC_i = \frac{STEC_i}{\sqrt{1 - \left(\dfrac{R_e}{R_e + h}\sin z_i\right)^2}} \qquad i = 1, 2 \tag{2}$$

R_e represents the mean radius of the Earth and h is the assumed height of the ionospheric layer as plotted in figure 1. The intersection point of the ray path with the ionospheric shell is called the sub-ionospheric point and defines latitude and longitude of a VTEC value.

2. Comparison of $\Delta STEC$ Values from VLBI and GPS

$\Delta STEC$ values derived by VLBI and GPS were compared for various VLBI sessions of the CORE-A and EUROPE networks. There is a good agreement for medium length baselines (500 –

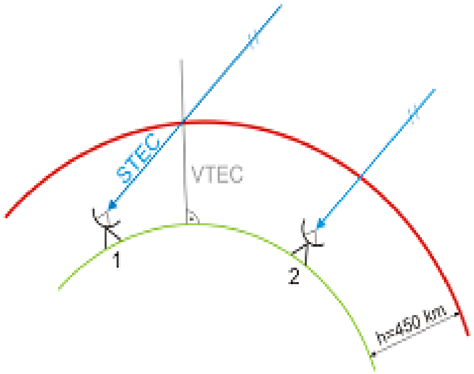

Figure 1. Single layer model

2000 km) with correlation coefficients $r > 0.7$. For baselines longer than 2000 km the correlation is even higher ($r > 0.9$) which was also shown by Sekido et al. (2001) [6]. In figure 2 $\Delta STEC$ values of the baseline Wettzell-Yebes are plotted, obtained during the VLBI EUROPE session on May 15th, 2000. The values from both techniques are obviously highly correlated and the offset, contained in equation (1), can be seen. If absolute STEC values of one station are known it is possible to derive STEC values of the other station (or of all other stations in a multi-station network). It has to be considered that the accuracy $\sigma_{\Delta STEC}$ of absolute values mainly depends on the determination of the unknown offset per baseline (see equation 1) and can be expressed by

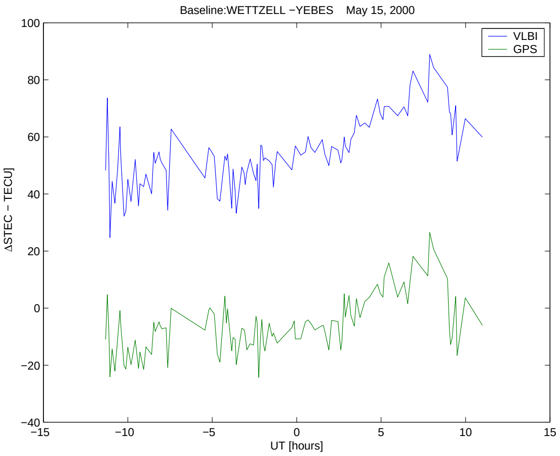

Figure 2. $\Delta STEC$ from VLBI and GPS

$$\sigma_{\Delta STEC} = \sqrt{\sigma_{meas}^2 + \sigma_{offset}^2} \tag{3}$$

with

$$\sigma_{meas}^2 = \frac{\sigma_{\tau_X}^2 + \sigma_{\tau_S}^2}{40.28\left(\frac{1}{f_X^2} - \frac{1}{f_S^2}\right)} \tag{4}$$

σ_{τ_X}, σ_{τ_S} are the standard deviations of the observed group delays τ_X, τ_S, and σ_{offset} the standard deviation of the offset obtained by the least-squares fit described in step 1 of section 3.

3. Determination of Absolute STEC Values from VLBI

As described in the previous section external information (from GPS, Ionosondes, Incoherent Scatter Radar, Faraday rotation measurements) is needed to calculate the unknown baseline-dependent offsets and to compute absolute STEC values. In this work GPS VTEC values provided by the International GPS Service (IGS), and given in ionospheric exchange format (IONEX, Schaer et al., 1998 [5]), were used. Based on this information STEC differences ($\Delta STEC$) were calculated and compared with VLBI derived values. Under the assumption that the offset per baseline did not vary during an experiment the following procedure was applied (see flow chart, figure 3).

1. Once a day (when the mean elevation at all stations reaches a maximum) all offsets in a network were fixed by the use of the $\Delta STEC$ values derived by GPS. This requires GPS receivers on every station or global models like IONEX. A least-squares fit under the condition that the sum of the offsets in a triangle equals zero, which can be written in the form

$$offset_{12} + offset_{23} + offset_{31} = 0 \tag{5}$$

   was carried out to estimate the unknown offsets. The mean variances of the offsets are ± 1-2 TEC units.

2. For the calculation of absolute values one site was chosen as reference station for which the IONEX data were fixed (VTEC values stored in a geographical grid for every 2 hours were transformed into STEC values).

3. By a shortest path Dijkstra algorithm the path from the reference station to every other station in the network was calculated. By adding the sum of $\Delta STEC$ values along the path to the fixed value, absolute STEC values of each site were obtained.

4. These STEC values were transformed into VTEC numbers so that they can be compared with results from other techniques.

5. The TEC measurements allow derivation of ionospheric maps for areas with dense VLBI networks, e.g. over Europe. For that purpose the EUROPE VLBI sessions were used with seven to ten stations observing simultaneously. We have to assume that the temporal and spatial variations of the ionosphere are small to gain more data. Therefore data from a time span of T ± 3 hours were used for each time epoch T for producing high resolution maps. The geographic coordinates of the sub-ionospheric point related to a VTEC value were rotated around the geomagnetic north pole. The rotation angle needed for this step equals the time span between the time of observation and the reference time T.

6. In *static ionospheric mapping* the VTEC values are arranged by an interpolation algorithm on a rectangular grid that represents the status of the ionosphere for a certain time. As an example a regional VTEC map derived from the VLBI EUROPE session on December 13, 1999 is shown in figure 4, left. The results agree rather well with the VTEC map derived by GPS for the same epoch (figure 4, right).

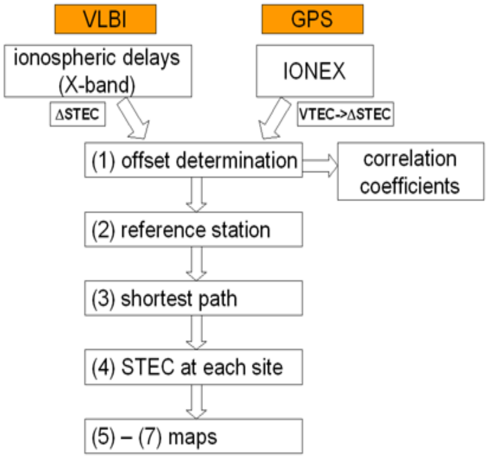

Figure 3. Flow chart of the determination of ionospheric parameters by VLBI

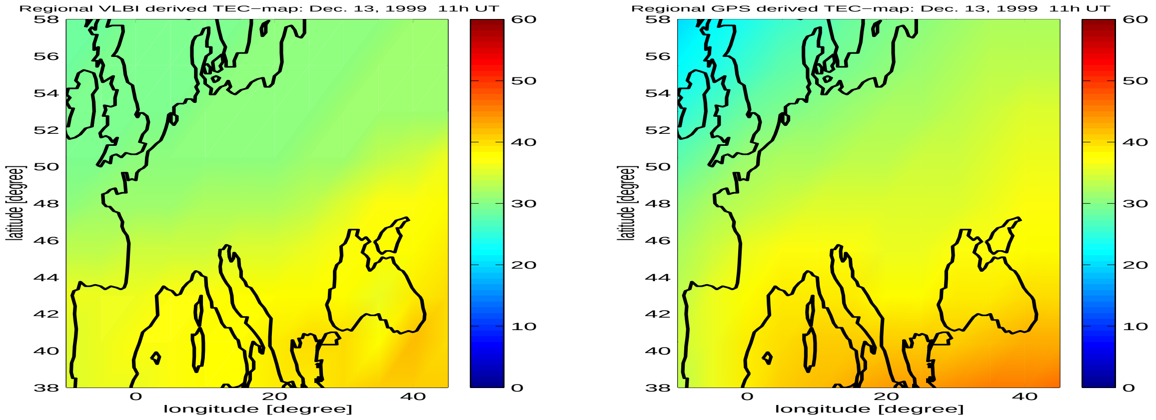

Figure 4. Regional VTEC maps from VLBI (left) and GPS (right)

7. In *dynamic ionospheric mapping* such maps dependent on time are produced. Animated maps are obtained that allow conclusions on temporal and spatial behaviour of the ionosphere over a certain region.

4. Conclusions

First results show good agreement between VLBI and GPS relative STEC values. A method was developed to determine absolute VTEC values from VLBI with calibration by any external measurement or model. Static and dynamic VTEC maps can be computed from sufficiently dense VLBI networks and these maps can be compared with results from other techniques.

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