# Ionospheric Disturbance Indices for RTK and Network RTK Positioning

Lambert Wanninger
*Geodetic Institute, Dresden University of Technology, Germany*

## BIOGRAPHY

Lambert Wanninger received his Dipl.-Ing. and his Dr.-Ing. in Geodesy from the University of Hannover, Germany. He spent several years at Dresden University of Technology working in the field of GPS. In 2000 he founded Ingenieurbüro Wanninger, which develops software for precise GPS applications. Recently he rejoined Dresden University of Technology as a professor in the Geodetic Institute.

## ABSTRACT

Ionospheric disturbances may cause difficulties in single-base RTK and even in Network RTK positioning. Hence, index values providing statistical information on expected residual ionospheric biases are of great help to RTK users. One such indicator is the $I_{95}$ ionospheric disturbance index which has been in continuous use in Central Europe since 1998. This 7 year long time series contains valuable statistical information on the occurrence of medium-scale and small-scale ionospheric disturbances. Whereas the $I_{95}$ index is mainly suited for RTK positioning, a newly developed $I_{95L}$-index is aimed at Network RTK users. Numerical values of both indices are compared.

## INTRODUCTION

Single base RTK is limited to short distances between the reference receiver and the rover receiver due to distance dependent biases, mainly caused by ionospheric refraction. During time periods of small differential ionospheric effects, RTK may be used for baselines of up to 20 km and beyond. In the presence of ionospheric disturbances, however, RTK is limited to maximum station distances of just a few kilometers.

In recent years Network RTK has been proven to be able to mitigate these RTK limitations (Wanninger 1999, Rizos and Han 2002). Based on the observations of a network of reference stations with station spacing of 50 to 80+ km, a large portion of the differential ionospheric biases can be modeled and removed. Hence, the use of RTK is extended from the surrounding of a single reference station to a large area covered by a reference station network. But unfortunately, in the presence of small-scale or medium-scale ionospheric disturbances large ionospheric residuals remain even with Network RTK.

Therefore, indicators of the expected size of the residual ionospheric errors are of great importance for users of single base station RTK and also for users of Network RTK. Such indicators fulfill two tasks. First, they inform about expected difficulties in RTK or Network RTK positioning, so that a user is able to react accordingly. And secondly, they may be able to support baseline ambiguity resolution by providing statistical information on the expected size of residual ionospheric biases.

One such indicator is the $I_{95}$ ionospheric disturbance index which was developed in 1998 (Wanninger 1999) and which has been in continuous use in Central Europe ever since. The $I_{95}$ index is based on the differential ionospheric residuals as computed in a network of GPS reference stations. Originally intended to support single base station RTK only, it also proved to be useful for Network RTK users. Today hourly $I_{95}$ index values are available from several internet web sites of Network RTK service providers in Europe.

Almost 7 years of continuous hourly $I_{95}$ values have been collected. They cover the years of maximum activity of solar cycle 23. This data base provides valuable statistical information of ionospheric effects on RTK positioning and also of the occurrence of medium-scale Traveling Ionospheric Disturbances (TIDs) and small-scale disturbances in Central Europe.

Proc. ION GNSS 2004, Long Beach, CA, 2849-2854.

## $I_{95}$ INDEX

With the installment of dense GPS reference station networks, precise correction models of distance-dependent biases, which are mainly caused by atmospheric refraction, could be produced for the first time. These correction models are based on the ambiguity-resolved carrier phase observations and are thus able to record differential atmospheric effects with millimeter to centimeter accuracy. The ionospheric models are produced for every individual satellite and with a high resolution in time.

In many realizations of precise ionospheric modeling in dense GPS reference station networks each correction model comprises of just two coefficients. They represent the differential ionospheric biases in two directions: south-north ($\Delta I_{LAT}$) and west-east ($\Delta I_{LON}$). Since these coefficients are produced for each available satellite signal and with a high resolution in time, several hundred such coefficients are estimated per hour.

The $I_{95}$ ionospheric index is based on these ionospheric model coefficients (Wanninger 1999). In order to condense their information content each two corresponding coefficients are combined by

$$\Delta I = \sqrt{\Delta I_{LAT}^2 + \Delta I_{LON}^2}$$

and thus any information on the direction of the differential ionospheric biases is removed. Then, the $I_{95}$ index is identical to the 95% margin of all $\Delta I$ values in a predefined period of time. It was decided to use such a 95% margin since it can be expected that GPS carrier phase processing softwares are able to select and neglect those observations which are affected most.

Hence, the $I_{95}$ index is a statistical figure providing information on the amount of differential ionospheric biases as they are experienced by users of differential GPS positioning. The index is computed from dual-frequency ambiguity-fixed carrier phase observations, which allow the estimation of the differential ionospheric biases with sub-centimeter accuracy (L1). A single $I_{95}$ value merges the differential ionospheric biases of all available satellite signals of at least 2 baselines (at least 3 reference stations) into a single number.

$I_{95}$ index values do not only depend on the ionospheric conditions but also on several other factors, as e.g.:

- GPS reference station distances and
- elevation mask angle.

All index values presented in this paper originate from networks with reference station distances of about 50 km.

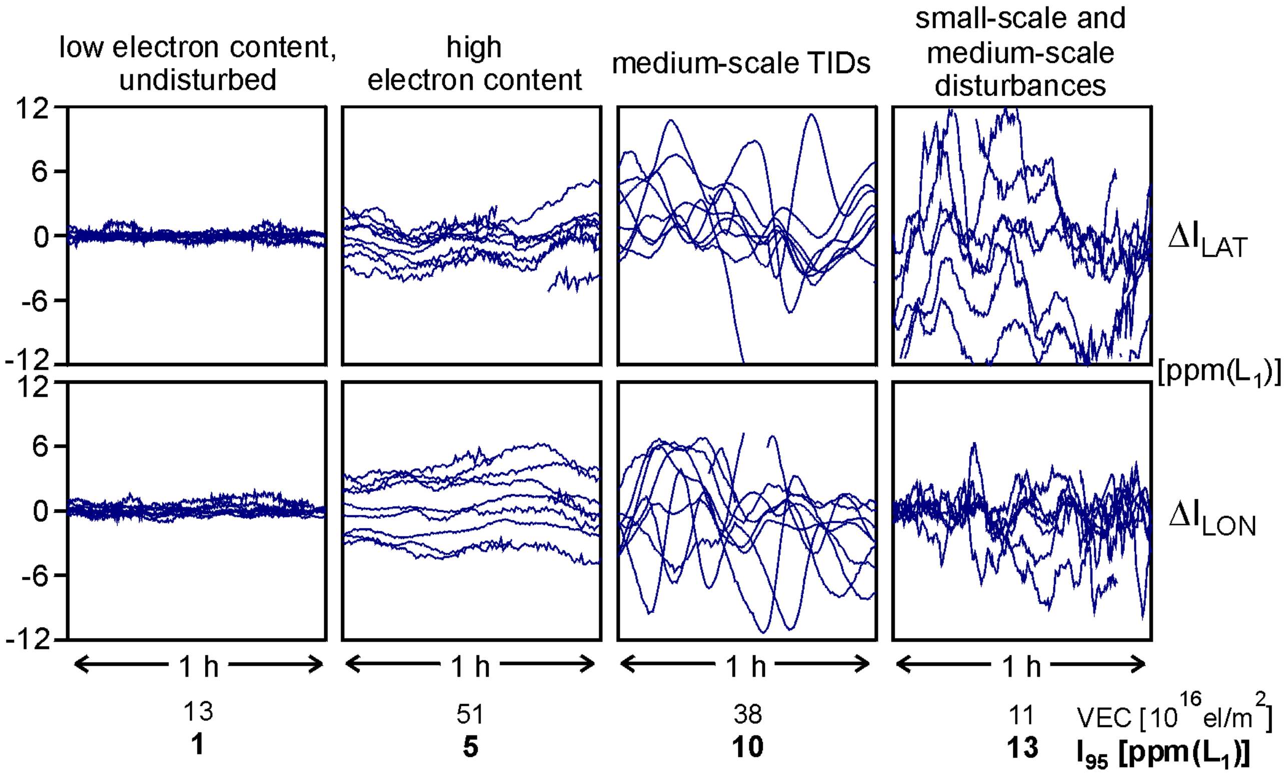

Fig. 1: Examples of ionospheric correction model coefficients $\Delta I_{LAT}$ and $\Delta I_{LON}$, and also of $I_{95}$ index values under various ionospheric conditions. Each line connects the coefficients of a single satellite.

When the processing of index values started in 1998 an elevation mask of 14 degrees was selected. This setting has not been altered in order to produce a consistent data set for a long period of time. Today an elevation mask of 10 degrees seems to be more appropriate since more and more users process the signals of satellites elevated less than 14 degrees. The $I_{95}$ values slightly increase when the elevation mask is lowered to 10 degrees.

Examples of ionospheric correction model coefficients $\Delta I_{LAT}$ and $\Delta I_{LON}$, and also of $I_{95}$ index values are shown in Fig. 1. Typical ionospheric situations in the mid-latitude region of Central Europe are:

- low electron content and undisturbed ionospheric conditions resulting in $I_{95}$ values of less or equal 2 units [ppm (L1)],
- high Vertical Electron Content (VEC) but no irregularities produce $I_{95}$ values of up to 5 units,
- medium-scale disturbances, which are the most common form of ionospheric irregularities in mid-latitudes, cause $I_{95}$ values of 10 or even more,
- small-scale disturbances may produce even larger index values but they are rarely experienced in mid-latitudes.

## COMPARISON OF $I_{95}$ INDEX VALUES FROM DIFFERENT NETWORKS

In recent years $I_{95}$ values were computed based on the GPS observations of two different sub-networks of the German SAPOS GPS reference station network. One of these sub-networks (to be referred to as SAN) consists of three selected reference stations, the minimum number of reference stations needed for the computation of network-based correction model coefficients. Another time-series of $I_{95}$ values originates from a four station sub-network (to be referred to as LGN). Here, the index is based on the observations of 4 stations in order to be able to compute $I_{95}$ values even in the case of a failure of one of the reference stations. The two sub-networks are separated by approximately 200 km (Fig. 2).

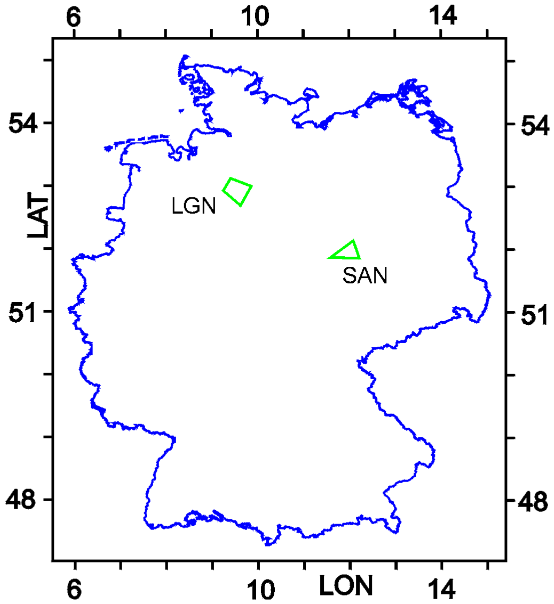

Fig. 2: Two sub-networks of the German SAPOS GPS-reference station network which are used for $I_{95}$ index value computation.

Hourly $I_{95}$ values from both sub-networks are available for 98.7 % of all hours of the year 2002. The comparison of the index values of SAN and LGN shows that they differ by less than 2 units for 96.5 % of all available index pairs (Fig. 3). This very high agreement proves that the index values are fairly independent of the individual reference stations used for their computation, at least as long as the station distances are of similar lengths. Furthermore, it proves that index values produced from the observations of one small sub-network provides statistical information on differential ionospheric effects even for RTK users being several 100 km apart.

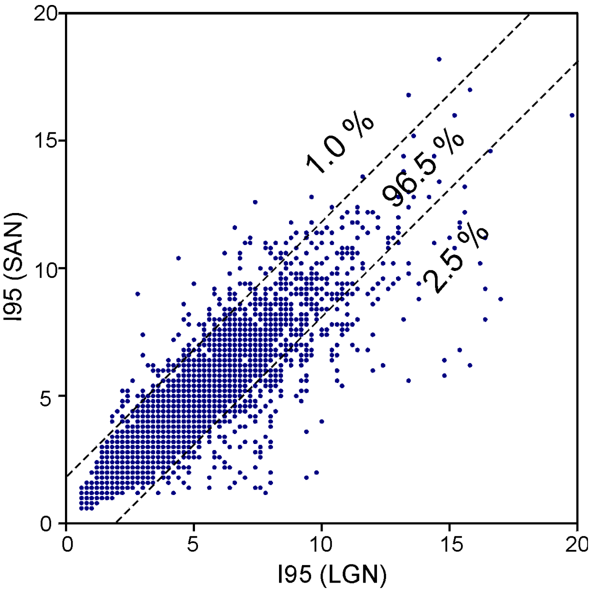

Fig. 3: Comparison of 8650 available hourly $I_{95}$ values (year 2002) from the two networks shown in Fig. 2.

## $I_{95}$ INDEX VALUES 1997 - 2004

More than 60,000 hourly $I_{95}$ values were computed from the GPS observations collected in the sub-network SAN (Fig. 2) in the years 1997 to 2004.

Figure 4 presents the 2002 subset in the form of diurnal variations sorted by months. 2002 was one of the years of maximum solar activity in solar cycle 23. Largest index values are found around local noon in the winter months (January to early March and less pronounced in November and December).

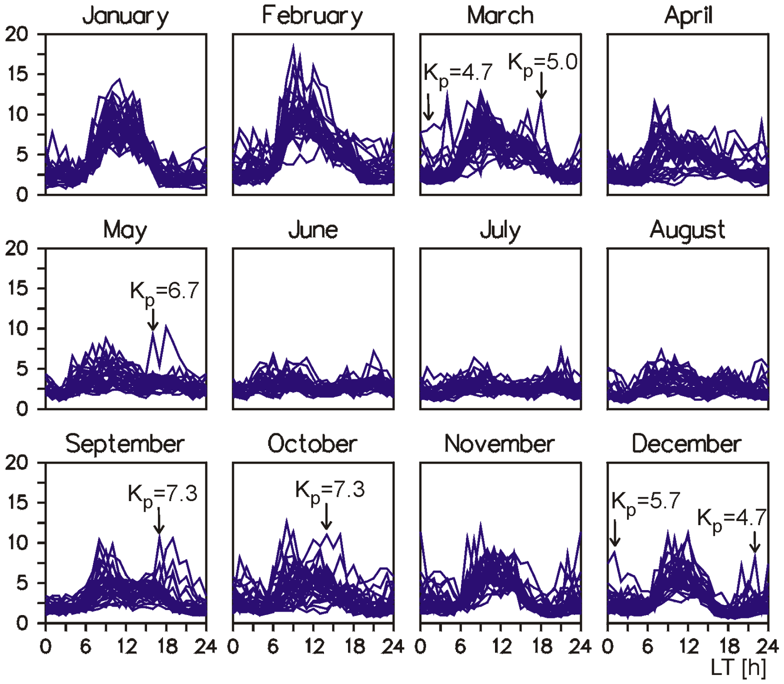

Fig. 4: Daily variations of $I_{95}$ index values sorted by months of year 2002. Kp values around 5 or larger indicate increased geomagnetic activity.

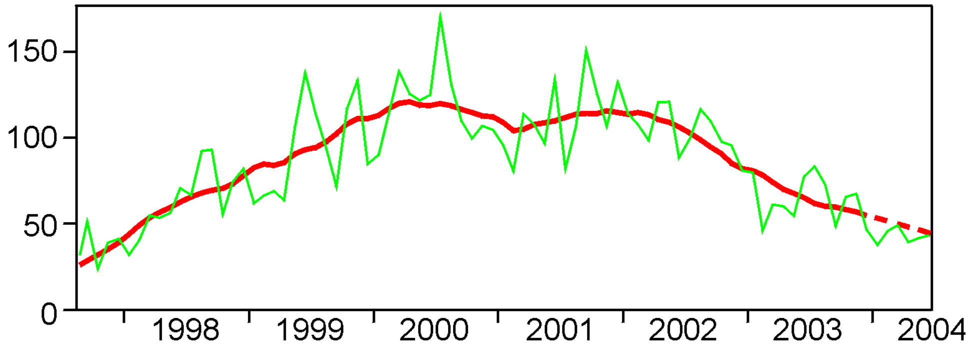

Fig. 5: Monthly and monthly smoothed sunspot numbers (SIDC 2004).

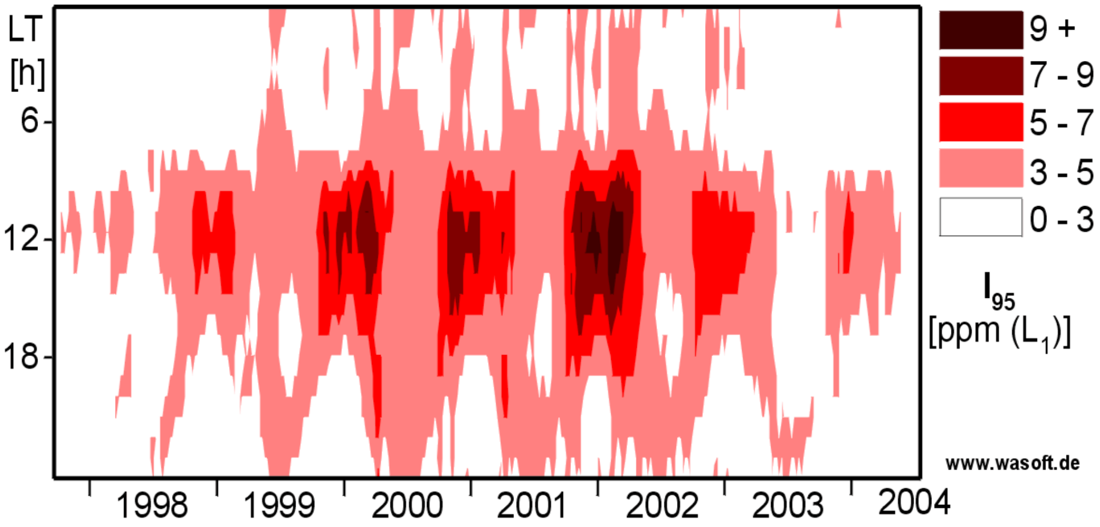

Fig. 6: Weekly averages of hourly $I_{95}$ index values calculated for the three station network SAN in Central Europe.

These ionospheric biases are mainly caused by medium-scale disturbances. Smallest index values are found from June to August. On some days the $I_{95}$ index values are much larger than the monthly mean values. In most of these cases an increased geomagnetic activity existed (see global Kp index values in Figure 4) which caused small-scale ionospheric disturbances affecting even this mid-latitude data. A high Vertical Electron Content (VEC) in the months around the equinoxes had small effects. More visible are the influences of large-scale gradients between 6 and 12 LT on some days in March, April, September, and October.

All $I_{95}$ values of 7 years were used to produce Figure 6. It shows weekly averages of these index values in a coordinate system of date and local time and covers most of solar cycle 23, especially the years of maximum solar activity (cf. Fig. 5). It confirms that in Central Europe the largest differential ionospheric biases occur in years of high solar activity in the winter months around local noon. These large ionospheric biases are mainly caused be medium-scale TIDs.

## $I_{95L}$ INDEX

The advantage of Network RTK over single-base RTK lies in the mitigation of the ionospheric biases affecting ambiguity resolution and position accuracy. The ionospheric correction models of Network RTK remove (at least) the linear part of the differential ionospheric biases. Hence, what remains is the non-linear part and thus an ionospheric index for Network RTK must be an indicator for the non-linearity of the differential ionospheric biases.

In recent years several ionospheric indicators for Network RTK have been suggested (Chen et al. 2003, Wübbena et al. 2004). All these indicators estimate the remaining ionospheric biases which affect the Network RTK positioning of a rover receiver. These indicators are based on e.g.

- the standard deviations of the linear ionospheric correction model coefficients when computed from the observations of several (sufficiently more than 3) surrounding reference stations,
- ionospheric residuals computed for an additional reference station which has been omitted in the computation of the correction models and serves as a monitor station.

Following the second approach the ionospheric Network RTK index $I_{95L}$ is computed from a 4 station sub-network with the ionospheric correction model being based on the observations of 3 surrounding reference stations and a fourth station being used as a monitor station (cf. Fig. 7).

In a first processing step correction model coefficients for the ionospheric (and geometric) differential biases are computed from the observations of the 3 surrounding reference stations. Then, these model coefficients are used to produce Virtual Reference Station (VRS) observations for the position of the monitor site. In a third step the baseline between VRS and monitor station is processed (dual-frequency ambiguity fixing), so that ionospheric double-difference (DD) residuals are obtained. These residuals are mainly caused by the remaining ionospheric biases. They also reveal the quality of the ionospheric correction models.

In further processing steps the ionospheric DD residuals are scaled to ionospheric effects on $L_1$-observations and a single index value for a specific time period (usually 1 hour) is obtained by a statistical evaluation of all DD values: the $I_{95L}$ index is defined as the 95% margin of all these DD residuals.

The $I_{95L}$ index values do not only depend on the ionospheric conditions but also on several other factors, as e.g.:

- GPS reference station network geometry and
- elevation mask angle.

The index values presented here originate from a network with reference station distances of about 50 km and the monitor station being close to the center of the triangle which is formed by the 3 surrounding reference stations (Fig. 7). A 14 degree elevation mask angle was used.

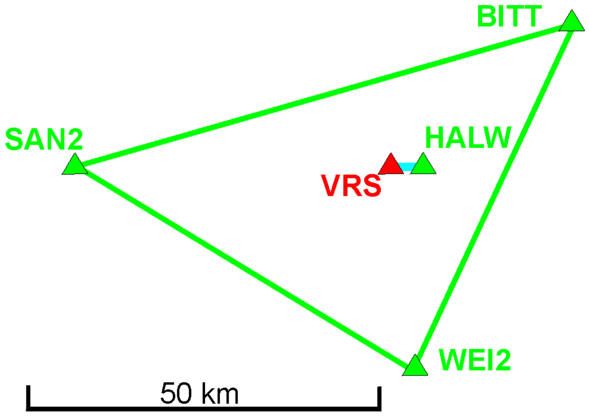

Fig. 7: A 4 station sub-network used for the computation of the ionospheric Network RTK index $I_{95L}$.

## COMPARISON OF $I_{95}$ AND $I_{95L}$ INDEX VALUES

One year (1999) of observations of the 4 station reference sub-network presented in Fig. 7 were processed in order to be able to compare $I_{95}$ and $I_{95L}$ index values. The ionospheric correction model coefficients are based on the observations of the surrounding 3 reference stations. These coefficients were used to compute $I_{95}$ index values

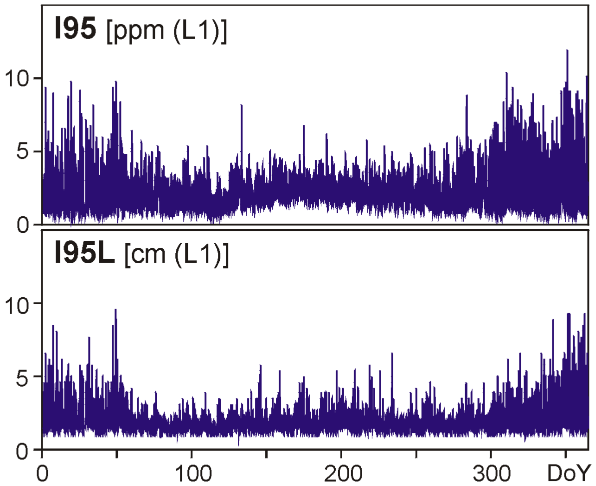

Fig. 8: All 1999 hourly $I_{95}$ and $I_{95L}$ index values from the network shown in Fig. 7.

and also the VRS observations for the monitor station site. Finally, $I_{95L}$ index values were obtained from the baseline processing between VRS and monitor station.

The two indices are supposed to provide information on different characteristics of differential ionospheric biases, but nevertheless the 1999 time series of $I_{95}$ and $I_{95L}$ have a lot in common (Fig. 8). First of all, but rather accidentally, both indices have values in the range of 0 to 10+. Secondly, both time series show the anomaly of large values during day-light hours in winter months (Fig. 8, Fig. 9). As mentioned before, the occurrence of medium-scale TIDs during day-light hours in the winter months affects both kinds of positioning, single-base RTK and Network RTK.

The largest differences in the two time series are found around the equinoxes (Fig. 8, Fig. 9). During these weeks high VEC and large-scale horizontal gradients in the electron content affect single-base RTK and also the $I_{95}$ index. These effects however are successfully modeled and removed by Network RTK and thus the $I_{95L}$ index values remain fairly small.

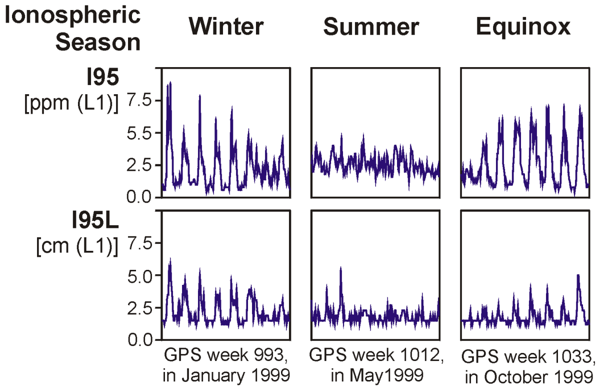

Fig. 9: Hourly $I_{95}$ and $I_{95L}$ index values of three selected weeks in 1999 from the network shown in Fig. 7

## CONCLUSIONS

Ionospheric disturbance indices provide valuable statistical information to single-base RTK and Network RTK users on expected residual ionospheric biases. 7 years of hourly $I_{95}$ index values reveal that in Central Europe the largest differential ionospheric biases occur in years of high solar activity in the day-light hours of the winter months. These large ionospheric biases are mainly caused be medium-scale Traveling Ionospheric Disturbances (TIDs).

These medium-scale disturbances also lead to large $I_{95L}$ index values. Whereas $I_{95}$ (single-base RTK) and $I_{95L}$ (Network RTK) time series show similarities in the mid-latitude ionospheric seasons winter and summer, they differ, however, around the equinoxes when the effects of high Vertical Electron Content (VEC) and large-scale horizontal gradients of VEC are successfully modeled and removed by Network RTK.

## ACKNOWLEDGMENTS

Most of the $I_{95}$ index values presented in this paper were computed at the state survey departments of Sachsen-Anhalt, Halle (Germany), and Niedersachsen, Hannover (Germany). The author is grateful for the generous support he received from the staff of these departments.

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