Higher order ionospheric effects on GNSS positioning in the European Region

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Introduction: Higher (second and third) order ionospheric effects (Ion2 and Ion3, respectively) in the European region during the active (2001), quiet (2006) and post-peak (2003) periods of the solar cycle are studied in this work (Fig.1).

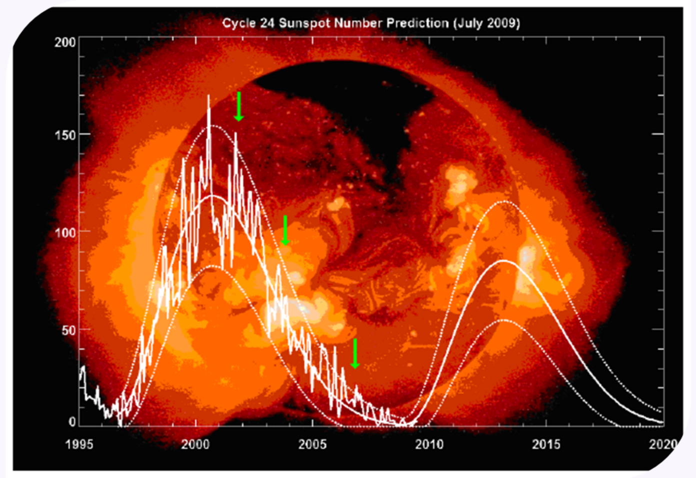

Figure 1. Sunspot cycle (NASA 2008)

Figure 2. IGS stations in this work

Using the ionosphere-free observable to eliminate the first order ionospheric effect on GNSS measurements leaves in Ion2 and Ion3, which cause residual range errors (RREs) in GNSS positioning.

High accuracy (cm-mm level) GNSS applications like Network RTK and Precise Point Positioning (PPP), need to account for RREs due to Ion2 and Ion3.

Stations in this work are selected from the International GNSS Service network in Europe considering a geographical distribution in latitude (mid, high and auroral) and longitude (Fig. 2).

Days for analysis were selected in terms of the planetary K index, K_p. In 2001 and 2006, days with $K_p < 4$ represent the effect of the solar activity on the ionosphere excluding any underlying geomagnetic disturbances. In 2003, days with $K_p \geq 4$ represent the combined effect of the solar activity and geomagnetic disturbances (NOAA 2005).

The program Rinex_HO (Marques et al. 2007):

- calculates RREs due to Ion2 and Ion3,
- outputs the total electron content (TEC) along the line of sight for each receiver-satellite link
- generates new GPS observation files corrected for Ion2 and Ion3.

The corrected GPS observation files enable to assess the influence of Ion2 and Ion3 in estimating the station coordinates in PPP which is performed with the Bernese Software 5.0 (BSW, free network solution) and the Canadian Spatial Reference System PPP tool.

Solar Activity and Ionosphere: The incoming charged solar particles in the solar flares can be routed to the lower altitudes of the ionosphere by the high latitude magnetic field lines where upon colliding with the ionospheric particles, they alter the ionospheric electron content (Rasinkangas 1998) (Fig. 3).

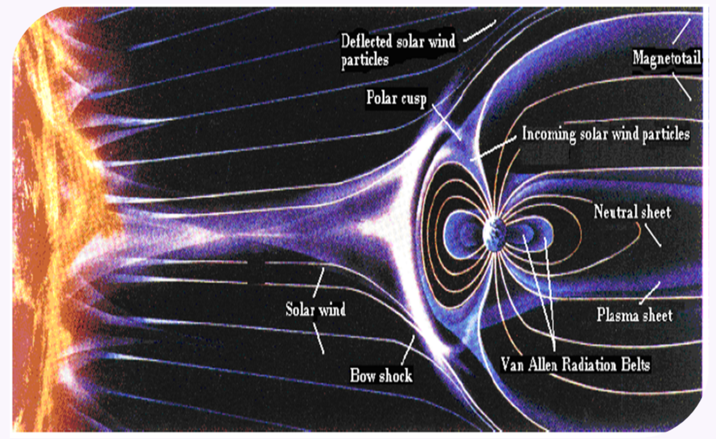

Figure 3. Solar flares in vicinity of the Earth (NASA)

Ionospheric free electrons and ions affect the velocity of the GNSS signals leading to the "Group delay" and "Phase advance" (Bassiri and Hajj 1993).

Ionospheric effects on the GNSS signals: The ionosphere causes a delay that varies according to (Hammad 2004):

- solar activity and sunspot number
- day of year (DOY) and time of day
- TEC along the signal link (STEC – the Slant TEC)
- GNSS carrier frequency
- geographic location of receiver

TEC, which is about 20-50 TECU at mid-latitudes (equivalent to a 3-8 m range delay on L1) during low solar activity, can be as high as 120-150 TECU during high solar activity, causing about 20-25 m delay on L1 (Clynch 2001).

From the Appleton-Hartree formula which describes the ionospheric phase refractive index (Budden 1966), Ion2 and Ion3 can be obtained as ($\kappa = 40.3\ m^3/s^2$):

$$n_{\pm}^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y_{\perp}^2 \pm \sqrt{Y_{\perp}^4 + 4(1-X)^2 Y_{\parallel}}}$$

$$Ion2_{gr,i} = \frac{\kappa e B_0 \cos\theta}{\pi m_e f_i^3} STEC$$

$$Ion3_{g,i} = \frac{3\kappa^2}{2 f_i^4} \eta N_{max} STEC$$

♦Ion2 depends on the projection of the geomagnetic field onto the signal path ($B_0 cos\theta$) at the ionospheric pierce point (IPP) (Fig. 4).

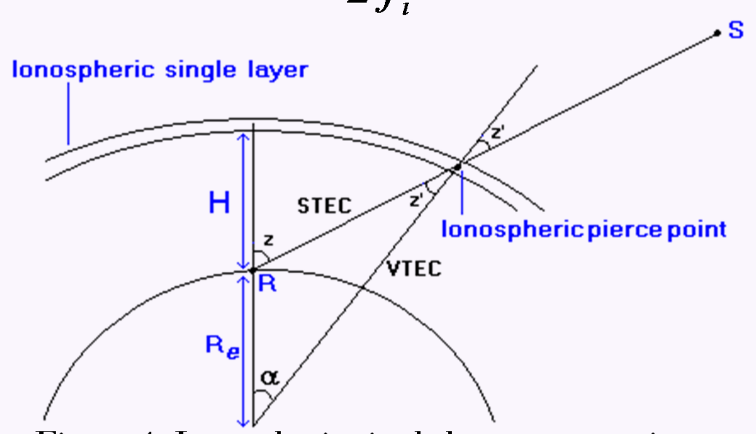

Figure 4. Ionospheric single layer assumption

♦ Ion3 depends on the shape parameter, η, and the maximum electron density in the ionosphere, N_{max}, that is assumed to occur in a single layer (at height H=450km) pierced at the IPP by the satellite -receiver link (Fig. 4).

STEC values can be obtained from pseudoranges, PR; this requires to input the receiver and satellite differential code biases (DCBs) which are about 5-10ns error sources (Bernese V5 Manual, 2007):

$$STEC = \frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)} \left\{ PR_1 - PR_2 - c(DCB_{rec} + DCB^{sat}) + \varepsilon_{1,2} \right\}$$

The uncertainty in STEC is given by the error propagationlaw:

$$\sigma_{STEC}^2 = \left(\frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)} \right)^2 . \left(\sigma_{PR1}^2 + \sigma_{PR2}^2 + c^2 \sigma_{DCBrec}^2 + c^2 \sigma_{DCBsat}^2 \right)$$

Marques et al. (2007) estimate the uncertainty in STEC according to the error propagationlaw as:

σ_{STEC}^2 (from PR) ~ 11 TECU

However, according to Pajares et al. (2008a):

σ_{STEC}^2 (from GIM) ~ 2-8 TECU

Therefore Global Ionospheric Maps (GIM) are used for STEC computation instead of pseudoranges in Rinex_HO, which converts the vertical TEC (VTEC) data from GIM into STEC using a single layer mapping function.

Results: Ion2 and Ion3 on L2 carrier (lower the frequency, larger the effect) are plotted for each station in order to:

- observe the latitudinal and diurnal variations of RREs
- investigate possible RREs dependency on the geomagnetic storms and level of background solar activity.

Accounting for the higher order terms of the ionospheric error affects the height component of the estimated position more significantly than the latitude and longitude components (Fig. 5).

Differences in PPP coordinate estimates (dlat, dlon, dh) fall within the centimeter level, corresponding to the sub-second level in the geodetic coordinates.

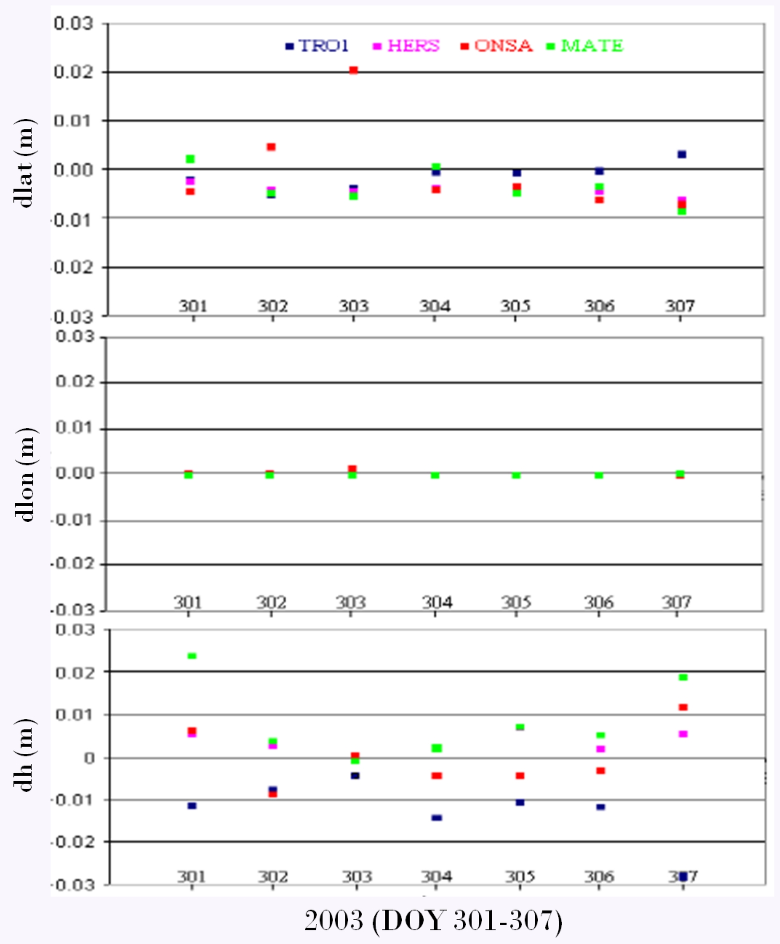

Figure 5. Differences in PPP results

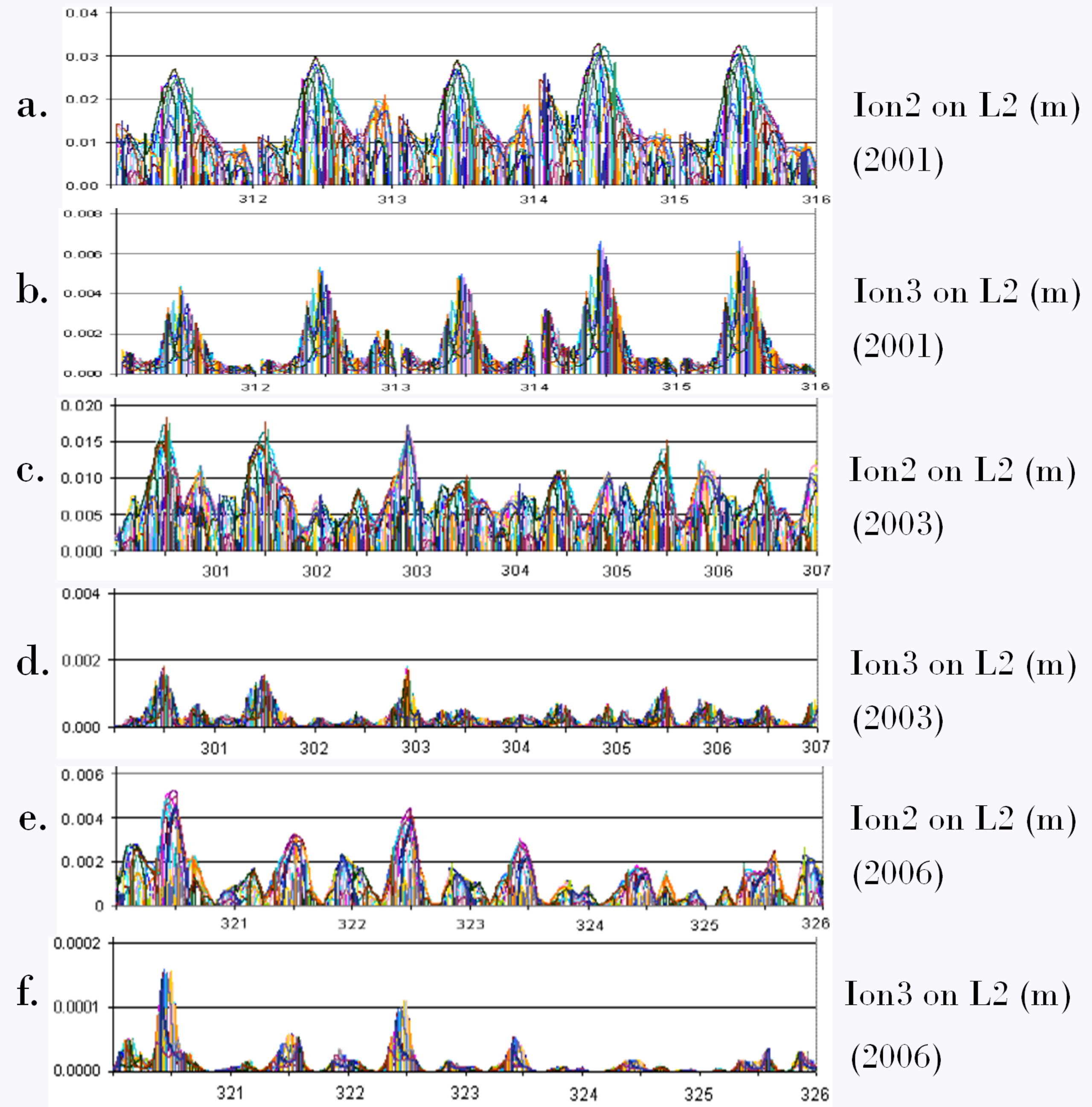

Figure 6. RREs (m) at Tromso during active (a, b), post-peak (c, d) and quiet (e, f) periods

During the active and post-peak periods of the solar cycle, Ion2 and Ion3 can cause cm-mm level RREs (plots a-d, Fig. 6) and night time RREs can be significant for the high latitudes. RREs due to Ion3 are in general an order of magnitude smaller than those due to Ion2 (plots e-f, Fig. 6).

Future work: How the new GNSS signals (GPS L5, L1C; Galileo E5, E6) can be used to more accurately estimate the higher order ionospheric errors or how these signals can be combined to actually eliminated these errors will be investigated in the future work.

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