Current status and expected improvements of ionospheric reprocessing

R.Orus, M.Hernández-Pajares, J.M. Juan, J.Sanz,
gAGE/UPC, Research group of Astronomy and Geomatics
Technical University of Catalonia
Barcelona, Spain
Contact e-mails: rorus@mat.upc.es, manuel@mat.upc.es

Abstract

The purpose of this work is to summarize the present status and expected results in the reprocessing of the IGS Global Ionospheric Vertical Total Electron Content Maps (GIMs), as a result of the official IGS call, happened in the beginning of 2006.

Indeed, the IGS GIMs are being computed since June 1998, see Feltens and Schaer 1998), as the weighted combination of the different GIMs processed by the involved agencies (presently CODE, ESA, JPL and UPC). During this time, the ionospheric techniques used by the agencies have experienced significant improvements: tomography, physical models, increase of temporal resolution, better interpolation techniques. These are some relevant improvements, introduced by different analysis centers. In such situation the backward recomputation of IGS GIMs, proposed in the context of the general IGS campaign, can provide a significantly better ionospheric product from IGS.

To illustrate that, we will summarized as well an approach based on the UPC interpolation algorithm, adapted from the Kriging technique, which allows not only the improvement of the UPC estimation, but the improvement of the ionospheric maps computed by other agencies as well, in a very simple and straightforward way. This fact could be quite convenient for the IGS reprocessing task. The first results obtained with this technique in the computation of the GIMs for the year 2000, show an improvement of 10% or more for practically all the analysis centers.

1. Introduction

In the 1st June of 1998 the International GNSS Service (IGS) started the deliberation of Global Ionospheric Maps (GIMs) computed with GPS data in a daily basis. This work was carried out by the Ionospheric working group, and more concretely by its IAACs (IGS Associate Analysis Centres), which were in that epoch: CODE, EMR, ESA, JPL and UPC. However, after additional improvements of GIM performances, a final IGS combined product was officially distributed at May 2003, see Hernandez-Pajares 2004, with a latency of 12 days. The accuracy of this final product was typically at least the same or better than the best individual GIM, but with higher availability and integrity.

In the last year, the IGS community has started the reprocessing of all its products with the up-to-date models and processing strategies, see Steigenberger et al. (2006) in this Proceedings. In this context, the ionospheric working group is not an exception and its products have suffered important improvements since 1998. These changes ranges from new interpolation strategies, such as ESA and UPC, changes in mapping functions as CODE, to simply the increasing number of GPS stations for all agencies. All of these improvements make the IGS maps be quite different from the old estimates and make sense for a reprocessing campaign.

Thus, in this work the recomputation of the IGS GIMs are studied for the first 2 months of the year 2000 in the framework of the IGS reprocessing pilot project. More concretely, the improvements of the UPC GIM are first studied comparing the performances of the different strategies, one of the main differences is basically the interpolation scheme, based on the International Reference Ionosphere (IRI interpolation, see Hernandez-Pajares et al. 1999), versus the use of Splines presently, and Kriging in the next future (see Orus et al 2005). The updating of the UPC strategy referred to the one used 6 years ago, implies an improvement of more than 50% on the vertical TEC estimation accuracy, and it shows more consistency in the DCB computation. Moreover, the possibility of improving the VTEC maps of any centre by applying the Kriging technique in a simple and straightforward way has been also studied for the same period of time. This approach shows an average improvement of about 20% for all the centres and about 5 – 10 % for the final IGS combined product.

2. GIMs reprocessing.

As it has been explained before, the main goal of this work is to show the improvement of the GIM reprocessing by means of updating the ionospheric modelling strategies of any IAAC. Firstly, the improvement of the UPC GIM is show in order to demonstrate the potential improvement of the centres when its own updated are applied to reprocess old data. Secondly, the performances of the improved GIMs by kriging are also shown to have an idea of the effect of all the reprocessing in the IGS final product. However, before starting to show the results several theoretical considerations have to be taken into account in order to understand the underlying recomputation technique used in this work. In this context, first of all the kriging technique will be exposed briefly, as in Orus et al. 2006, and then the technique to compute a levelled GIM-levelled TEC will be explained, since this last part gives the input data that will be used by the kriging technique for each GIMs reprocessing.

2.1 Kriging technique

The kriging interpolation technique was developed in the field of the geostatistics in the year 1950 by Krige, see Cressie 1992. This is a linear interpolator, see equation (1), in which the kriging technique computes the optimal weight that will be applied in our particular problem.

$$Z_0^{\,*} = \sum_{i=1}^{N} w_i \cdot Z_i \qquad (1)$$

Where Z_o^* is the value to interpolate, w_i is the weight to be applied to the sample data Z_i.

The main feature of this interpolation technique is that it can take into account the spatial correlation among the data used in the interpolation process by means of using the semivariogram *(g_{ij})* function, see equation (2). Thus, the semivariogram is the function that describes the spatial correlation among the data as a function of the distance.

In order to compute the weights, corresponding to each VTEC interpolation, specially needed in regions with lack of data, in order to give values at the grid points, the kriging equations have to be solved. In this work the ordinary kriging equations have been applied, which can be written as:

$$\sum_i w_i g_{ij} + l = g_{i0} \qquad (2)$$

Where w_i is the weight to be applied to the sample data, g_{ij} is the semivariogram at the given points and g_{io} is the semivariogram at the unknown points

In order to apply the ordinary kriging equation the mean values and standard deviation of the data should be independent of the location in order to assure the convergence of the method.

Then, in order to apply the ordinary kriging technique to the GIM estimation, it is necessary to fulfil several mathematical conditions. Basically, these conditions are referred to the independency of the data over the geographical location. This condition is achieved by means of interpolating the residuals over a certain base model; in our case the initial VTEC maps (or GIMs).

2.2. Obtaining a levelled vTEC from GIMs

In order to get direct STEC (and VTEC) measurements from a set of dual-frequency carrier phase measurements, from any GPS receiver, a reference global VTEC can be used to *level* the geometry-free combination of carrier phases. This allows as well increasing the ionospheric temporal TEC resolution, for instance 30 seconds as in the RINEX files. This high temporal TEC resolution data will be used as the main input for the reprocessing of the GIMs with the kriging technique, since this data will have the same bias as the former used GIM. Indeed in this framework, the vTEC maps are employed to align the geometry free or Ionospheric combination L_I, see equation 3, to compute the ambiguity term (B_I) for each continuous satellite - receiver arch of carrier phase data.

$$L_I = STEC + B_I \qquad (3)$$

Then, in order to compute the corresponding phase ambiguity for each satellite-receiver continuous arch, the STEC prediction of the vTEC map ($STEC_{vTEC}$) is computed over each satellite Ionospheric Pierce Point (IPP), and then the average is computed as follows:

$$< B_I >_i^{ja} = < L_{I\,i}^{\;ja} - STEC_{vTEC\,i}^{\;\;ja} > \qquad (4)$$

Where the indices i, j and α correspond to the receiver, satellite and arch indicator, and the average is performed over the corresponding continuous (no cycle slips) arch (α) of data.

With this estimation, the aligned STEC can be obtained:

$$STEC_{align_i}^{\;ja} = L_{I\,i}^{\;ja} - < B_I >_i^{ja} \qquad (5)$$

And the derived vertical TEC:

$$TEC_{align} = STEC_{align_i}^{\;ja} \cdot F_{IPP}^{\;-1} \qquad (6)$$

Where the F_{ipp} is, for example, the typical the "thin spherical layer" mapping function described by:

$$F_{IPP}(e) = \frac{1}{\sqrt{1 - \left(\frac{R_e}{R_e + h_{ion}} \cos(e)\right)^2}} \quad (7)$$

Where e is the elevation angle between the local receiver horizon and satellite LOS, h_{ion} the height of the thin layer, for instance 450km such is taken in IGS, and R_e is the Earth's radius.

Therefore, a levelled vTEC, with the low temporal resolution (instead of with the code), can be obtained over each IPP each 30 seconds.

3. Results for UPC

The first test that has been done involved the use of the UPC GIMs. In this framework, the technique used to generate this map is quite different from the one is employed nowadays. Thus, the performance has been computed with the TOPEX altimeter satellite, which orbits at 1330 km above the Earth' surface. This data is suitable for calibration purposes since the TOPEX VTEC is obtained from direct measurements of the dual-frequency altimeter over the oceans (typically far from GPS ground receivers). This constitutes a good external data source of reference to characterize the ionospheric maps accuracy in such "worst-case" scenario for GPS ionospheric maps. Therefore, the performance, computed as it was done in Orus et al 2002, is shown in figure 1.

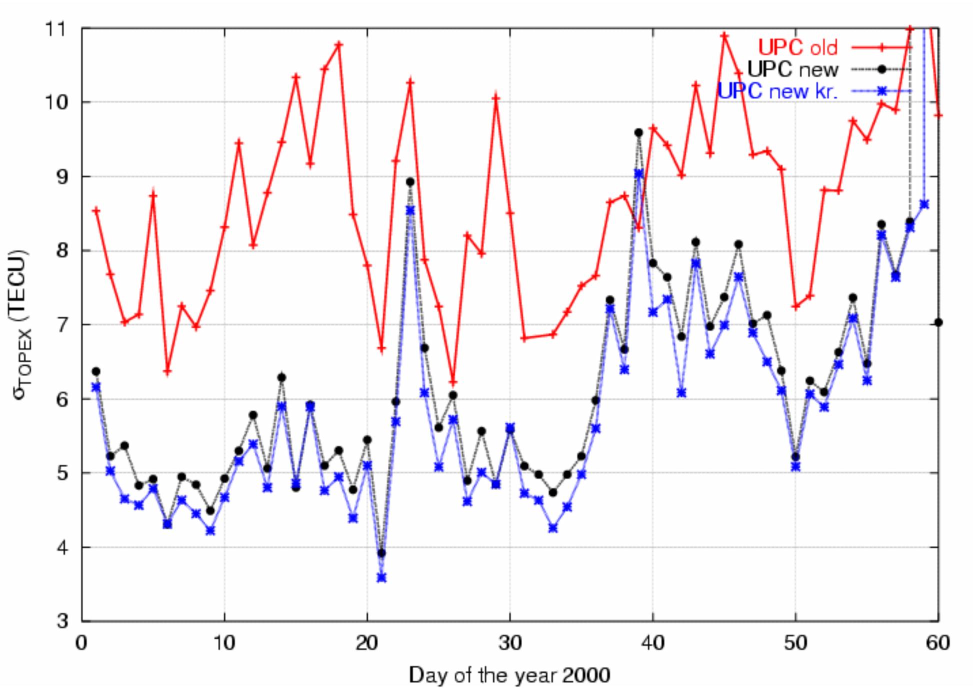

Figure 1: Standard deviation regarding to TOPEX data for the old UPC, current UPC and kriging UPC GIMs for the first 60 days of the year 2000.

In the figure 1, a very important improvement can be seen between the old UPC technique and the current one, the improvements range from 10% to 54% in the best cases.

In this context, it is interesting to take a look to the DCBs computation in order to see if there is an improvement on their estimation since they are computed in postprocessing, being a sub-product of the GIM computation.

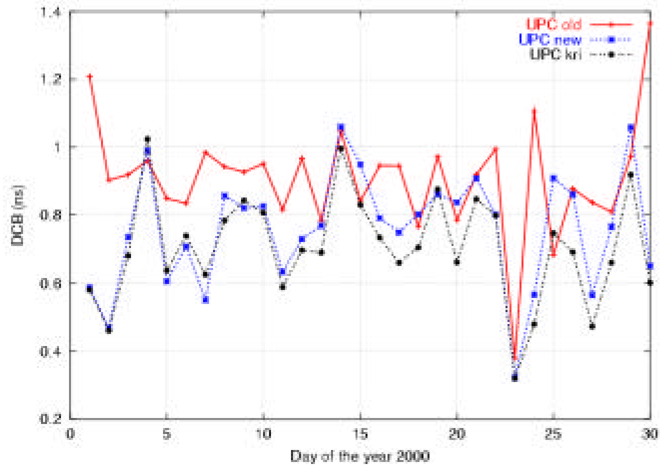

Figure 2: DCB estimation for PRN9 is depicted for the first 30 days of the year 2000.

It could be expected that the estimations of the DCBs would improve due to the fact that the GIM used to compute them are quite more accurate than the old ones. The situation is that the DCB are slightly improved by the new technique and, as can be seen in an example in figure 2, the kriging technique also adds a little variation in the DCB estimation.

4. Results for all GIMs

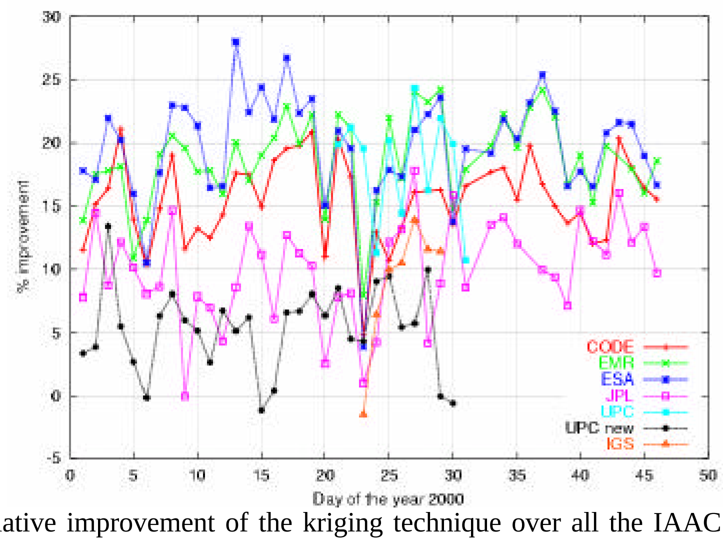

Figure 3: Relative improvement of the kriging technique over all the IAAC GIMs for the year 2000.

In this section we check the potential improvement of the recomputation for all IAAC GIMs. The kriging technique, see Orus et al. 2005, has been used in order to compute the GIMs for 10 days of the year 2000. First of all, the different GIMs have been used in order to compute a levelled VTEC (see section 2), which is the input of the kriging interpolation. Then, each GIM is used with their levelled VTEC in order to get the final map.

As it can be seen in figure 3 and figure 4, all the GIMs experience an improvement when the kriging technique is applied (the TOPEX VTEC measurements are taken again as the ground truth). Thus, if the improvement of the method is computed for all the days a mean improvement of about 10% is achieved, see figure 3, with a maximum improvement of 25%.

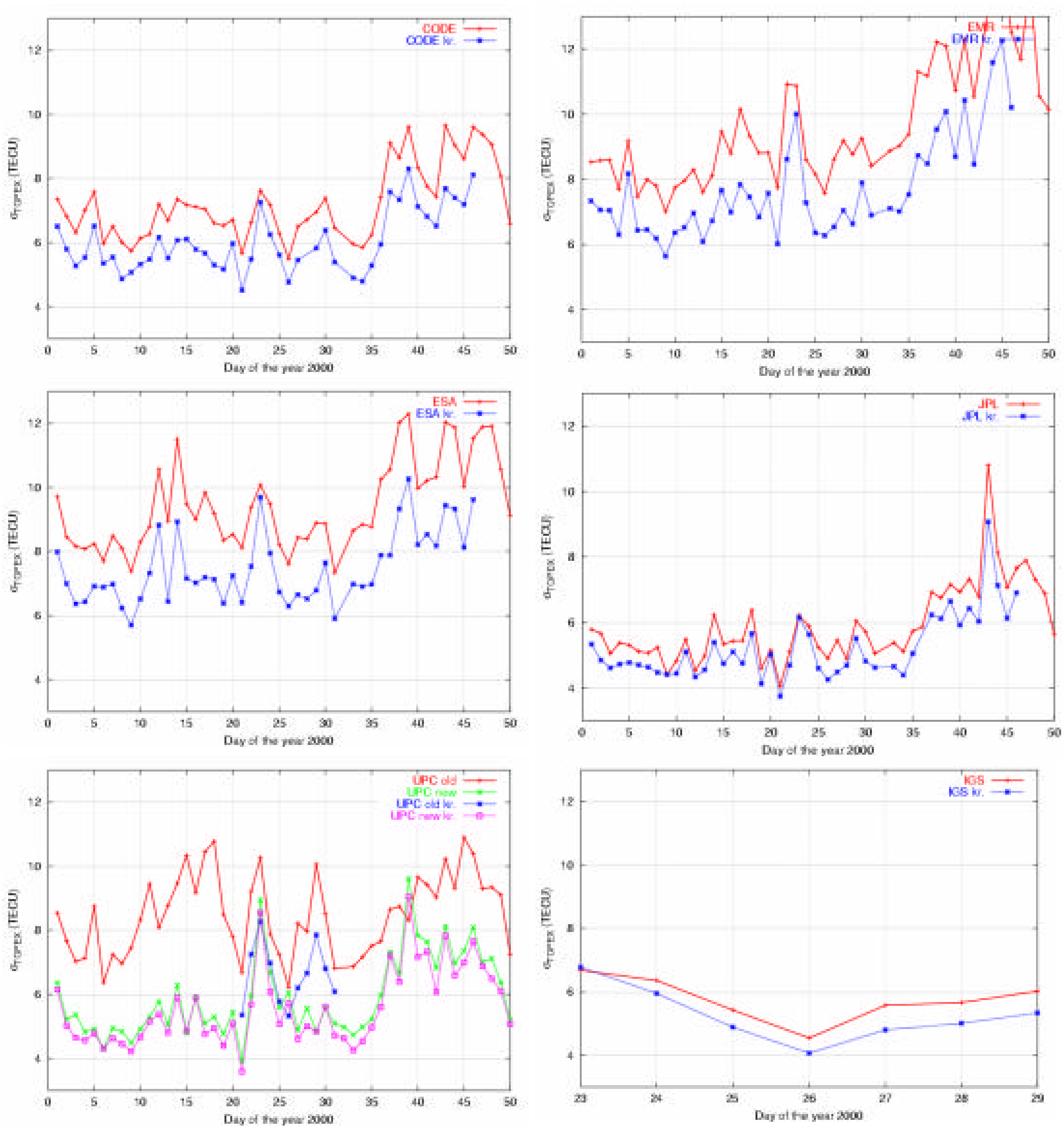

Figure 4: Comparison of accuracy between the old GIMs and the recomputing ones for all GIMs for the year 2000.

4.1. Performance over different regions

Once the overall performance has been tested, it is interesting to have a look to the regional performance of the GIMs, for instance, in the equatorial regions. In this zone we find both, high TEC gradients and lack of GPS data. As a reference we will compare as well in the Mediterranean region, which corresponds to a middle latitude zone, usually well covered by permanent GPS receivers. The first zone that is studied, as has been mentioned above, is the equatorial zone. The region comprises the Indonesia islands. The results are summarized in the following figure 5.

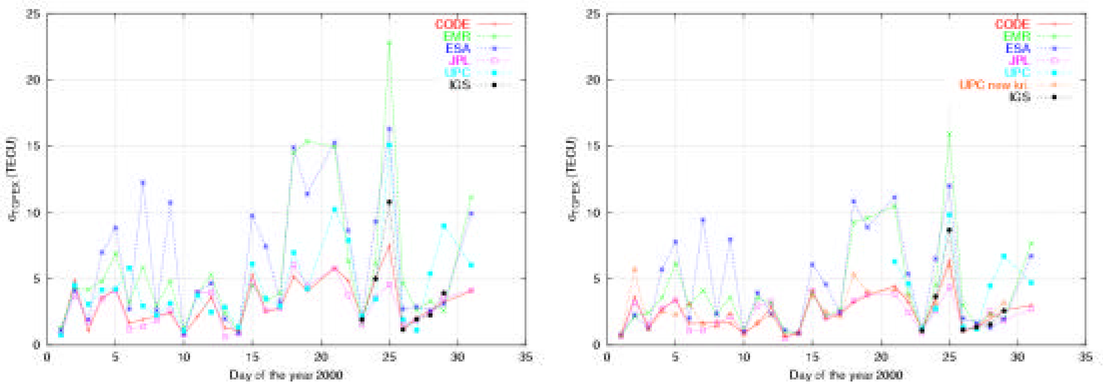

Figure 5: Both plots represent the performance of the GIMs over the Equatorial zone for the 30 first days of the year 2000, compared again to the TOPEX VTEC data: in the left hand side there are the official GIMs, and in the right hand side the recomputed ones.

As it can be seen in figure 6, the improvement reached, with the present procedures, in the equatorial zone is up to 5 TECU, and the impact of this improvement over the combined IGS maps is about 1-3 TECU.

The results for the Mediterranean zone are depicted in figure 6, and they show an improvement for all the GIMs, including the IGS one, of about 0.5 to 3 TECU.

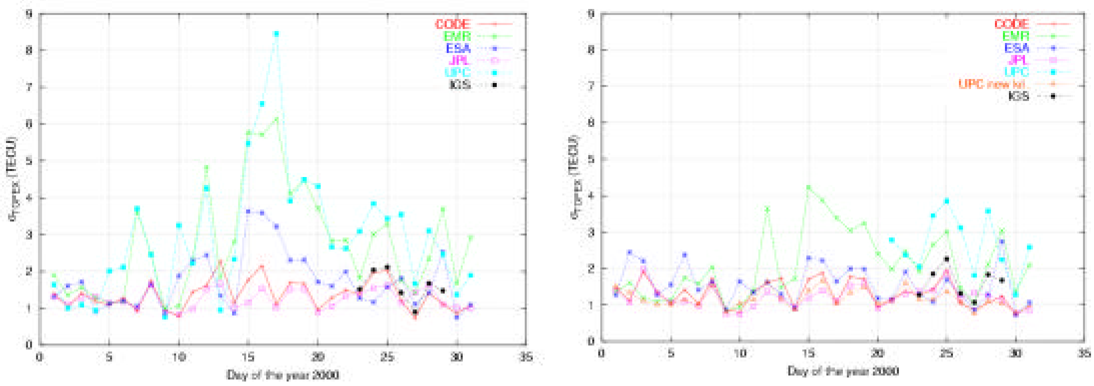

Figure 6: Both plots represent the performance of the GIMs over the Mediterranean zone for the 30 first days of the year 2000, compared again to the TOPEX VTEC data: in the left hand side there are the official GIMs, and in the right hand side the recomputed ones.

5. Conclusions

This work shows, in opinion of the authors, that the recomputation of the IGS ionospheric products, more concretely the combined IGS GIMs, has sense in terms of potential improvement. In this context, the reprocessing has been done by means of using the kriging interpolation technique. This technique has demonstrated that the improvements can reach up to 20% over the former GIMs. This recomputation has also benefit over the combined IGS GIM, showing a mean improvement of about 10% compared with the combined IGS GIM computed with the former GIMs. It has to be mentioned that it is expected a better improvements if the new IAACs techniques will used for the reprocessing campaign. In this context, the improvement achieved by the UPC, comparing the 2000 and 2006 techniques is up to 50% in accuracy.

Acknowledgements

The authors acknowledge to the International GPS Service and JPL the availability of the ground and TOPEX data sets respectively. This work has been partially supported by the Spanish project ESP-2004-05682-C02-01.

References

Cressie, N. (1992). *"Statistics for spatial data"*. Wiley, New York.

Feltens, J. and S. Schaer (1998): "*IGS Products for the Ionosphere*", IGS Position Paper, Proceedings of the IGS Analysis Centers Workshop, ESOC, Darmstadt, Germany, February 9-11, 1998, pp. 225-232.

Hernandez-Pajares M., J.M.Juan, J.Sanz (1999), *"New approaches in global ionospheric determination using gound GPS data"*, Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 61, 1237-1247, 1999.

Hernández-Pajares M., (2004) *"IGS Ionosphere WG Status Report: Performance of IGS Ionosphere TEC Maps (Position paper)"*, IGS Workshop, Bern, March 2004.

Steigenberger, P., Romero, I., Fang, P. (2006), Position Paper, "*Reprocessing Issues, Standardization, New models, IGS Workshop*", Darmstadt, May 2006.

Orus R., M.Hernandez-Pajares, J.M.Juan, J.Sanz, M.Garcia-Fernandez, (2002) *"Performance of different TEC models to provide GPS ionospheric corrections"*, Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 64, pp. 2055-2062, 2002.

Orus R., M.Hernandez-Pajares, J.M.Juan, J.Sanz, (2005) *"Improvement of Global Ionospheric VTEC Maps by using Kriging interpolation technique"*, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 67, Issue 16, November 2005, Pages 1598-1609.

Orus R., M.Hernandez-Pajares, J.M.Juan, J.Sanz, (2006) *"Improving Ionospheric determinations at UPC: Kriging and Wide Area RTK techniques"* Proceedings of IGS workshop 2006.