Ocean loading effects in a high time-resolution GPS analysis. Implications and artefacts analysis with GINS GPS software.

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ABSTRACT

Today's geodynamical and navigation applications of Global Navigation Satellite Systems (GNSS) are being used by a large variety of softwares where each one of them implements its own analysis strategy. The estimated parameters of a least squares (LSQ) procedure depend on these strategies (reference frame definition, troposphere parameterization, ambiguity resolution, receiver's antenna effect, stochastic parameterization, multipath etc.), which can induce artefacts in the estimated positions and velocities of geodetic points.

The aim of this study is to analyse the geodynamical results coming from the methodology used by GINS GPS software and propose a new methodology of ocean tide loading model validation. We are currently examining a double difference (DD) network solution together with the precise point positioning (PPP) strategy implemented in our software. To compare the strategy analyse, we use a set of 8 days from the 4 months GPS data acquired in north-western France Brittany, in 2004 in order to study ocean tide loading (OTL) (S. Vey et al., 2002). The ocean tides in this region can reach up to 10m and produce loading effects up to 12cm peak-to-peak on the vertical component and some cm-level displacements in the horizontal components of geodetic stations. In this specific case we need high time-resolution GPS solutions to study short-periodic signals (diurnal, semi-diurnal, third of a day, forth of a day, sixth of a day etc.) instead of classical 24h or weekly-average solutions. Moreover, the equivalence in some cases between the loading effect and the processing artefacts makes the processing strategy very sensitive to the analysis's criteria (ambiguity resolution, constraints, zenith troposphere path delay (ZTD), ad-hoc models etc.). For example in GRGS we are producing our own GPS orbits and a comparison of the solutions with the ones from IGS is examined through a regression analysis. So it is essential to quantify the strategy's impact on the GPS positioning. The different solutions are compared to the predictions resulting from the convolution of green's functions and amplitudes and phases of the FES2004 (F. Lyard et al., 2006) tide model, in a North-East-Up local geodetic reference system. Important conclusions on the M2, M3, M4, and M6 OTL modelling and their influence on the positions of geodetic markers are being made.

1. Introduction

The earth's crust undergoes periodic displacements due to temporally varying atmospheric, oceanic and continental water mass, surface loads. All these signals have a non negligible magnitude as far as it concerns geodetic applications of extreme precision (reference frame, positioning, orbits of low and medium earth orbiters etc.).

Different models describing the displacements of reference points due to various effects are already provided. The purpose of these models is to connect the regularised position of the geodetic points to their instantaneous positions (D. D. McCarthy and G. Petit, 2003).

Here we are mainly concentrating our studies to:

- the displacements of geodetic points caused by the ocean tide loading effect, in the north-western part of France, Brittany, and the investigation of a method of ocean tide loading validation,

- the impact of the different solution strategies, implemented in our GPS software, GINS, onto the estimated displacements via a regression analysis,
- the detection of loading effects of higher frequencies than those of sub-diurnal tides, (eg. M3, M4, M6).

The numerical model that we use, for ocean tide modelling, is the one from F. Lyard et al. FES2004, which is the product of assimilation of the altimetric data of ERS2, TOPEX/POSEIDON and the data of a global tide gauge network, into a hydrodynamic solution.

In the following sections we are analysing solutions of different strategies implemented with our software. Firstly, we are calculating our GRGS final GPS orbits and a validation with the ones from IGS, is being made. Secondly, we are estimating the time series of the campaign stations through a DD regional network analysis, where orbits are held fixed. In this section we are experimenting with different strategies like the fixation or not of ambiguities, the application of absolute or relative phase center variations, the usage of GRGS or IGS orbits etc. Together with the time series estimation, a spectral analysis is being made. Artefacts in relation with the strategy chosen and OTL signals not included in the model, start to become obvious. In the third section, we are realising a sensitivity analysis of modelled and estimated displacements where correlation coefficients and slopes are evaluated through a linear regression fitting, and the validation of the OTL model is effectuated. In the forth section, we are demonstrating preliminary results of a PPP method, implemented in our software. Due to the high frequency of the OTL signal that we want to observe, when using an absolute positioning mode, as is the case of PPP, we need high resolution clocks for the GPS satellites. In order to satisfy this constraint, we have used the 30s clocks of CODE analysis center, together with their orbits solutions for reasons of consistency. And finally, in the last part, we are discussing the relation between the true periodic signals from one side and the produced artefacts from the other.

2. *GPS orbit estimation*

In GRGS we are currently producing our own GPS orbits from a network of 70 permanent globally distributed IGS stations, which are shown in figure 1.

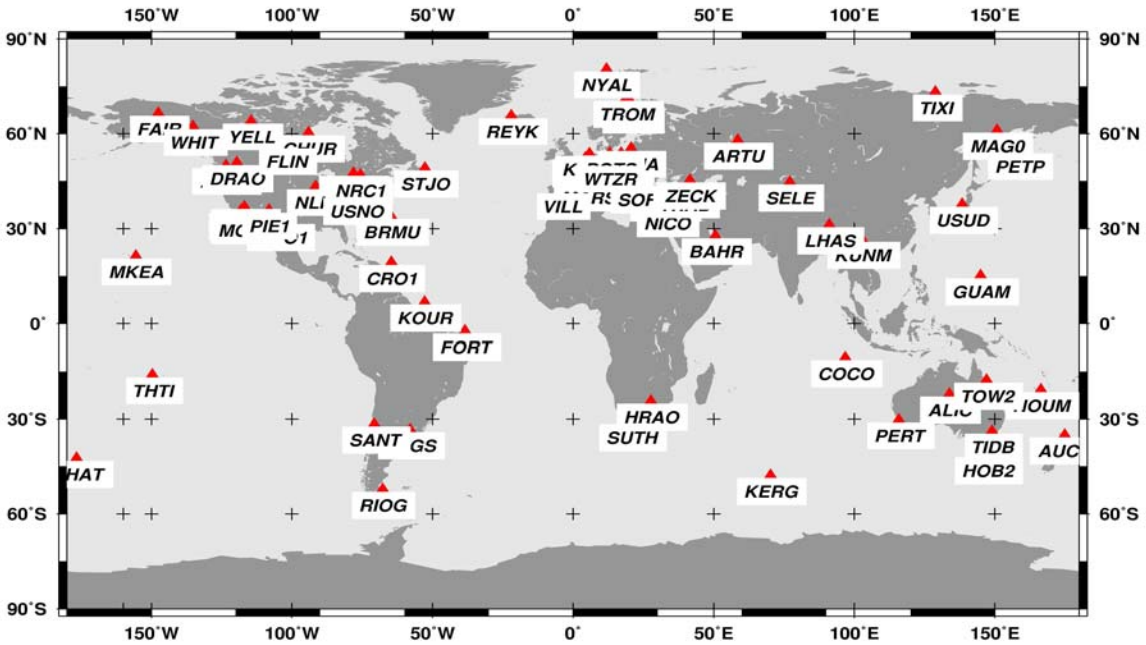

Fig. 1 : The network of 70 globally distributed IGS stations

For the purpose of our study, we are calculating 2 different solutions in function with the satellite-receiver phase center calibrations: one by applying the IGS_01 (relative corrections) model and the

other by applying the IGS_05 (absolute corrections) model (IGSMAIL-5189). We want to consistently compare with the IGS orbits, from one side, and from the other, to make internal comparisons and evaluate the impact of the new antenna models to the final estimates.
The processing strategy is summarised in table 1.

MEASUREMENT MODELS	
Basic observable	Carrier phase and code Elevation angle cut-off : 15° Sampling rate : 30s Weighting : 3.5 mm for phase and 35cm for pseudo-range
Modelled observable	Un-differenced iono-free linear combination (L3, P3)
RHC phase rotation corr.	Phase polarization effects applied (Wu et al., 1993)
Ground antenna phase center calibrations	Elevation – dependent phase center corrections are applied according to the models: IGS_01 (first solution) and IGS_05 (second solution). The relative corrections are given wrt. the Dorne Margolin T antenna.
Troposphere	A priori model : nominal constant; Mapping function: $\sin^{-1}$. Met data input : none
Ionosphere	Not modelled (eliminated by forming the iono-free linear combination of L1 and L2)
Plate motion	ITRF2000 velocities
Tidal displacements	Solid earth tidal displacement according to IERS 2003 conventions Pole tide : Applied to mean IERS pole position Ocean loading : Applied (FES2004 model)
Atmospheric loading	Applied from ECMWF pressure field every 6 hours
Earth orientation	EOPC04 IERS bulletin plus diurnal and semi-diurnal variations in x,y and UT1 models
Satellite center of mass	Block I x,y,z : 0.210, 0.000, 0.884 m Block II/IIA x,y,z : 0.279, 0.000, 1.026 m IGS_01 constant values for 1st solution Block IIR x,y,z : 0.000, 0.000, 0.000 m z-offset absolute values for individual satellites from IGS_05 for the 2nd solution
Satellite phase center calibration	1st Solution (IGS_01): not applied 2nd Solution (IGS_05) : applied
GPS attitude model	Nominal in a RTN frame with no yaw rate
Relativity corr.	Applied
ORBIT MODELS	
Geopotential	GRIM5_c1 degree and order 12 GM = 398600.4415 AE = 6378136.46 m
Third-body	Luni solar and planetary gravitation
Solar radiation pressure	Bar sever 1997 empirical model
Tidal forces	Solid Earth tides : IERS 2003 conventions
Numerical integration	Cowell's integration method based on a predictor-corrector type scheme with a fixed time-step. Tabular interval : 600s Arc length : 48 hours Inertial frame: J2000
ESTIMATED PARAMETERS (a-priori values and sigmas)	
Adjustment	Iterative weighted least squares scheme based on a first-order Taylor expansion of residuals and rms
Station coordinates	The IGS realisation of ITRF2000 (IGS00) is used
Satellite and receiver clock bias	Are estimated in the same time by using un-differenced data analysis. Satellite clocks : Initial values from broadcast ephemeris Receiver clock bias : Time estimated from pseudo-ranges (reference clock NRC1)
Orbital parameters	Initial parameters : position and velocity A-priori nominal values of the solar radiation pressure scale factor for every satellite. Final estimates: 6 keplerian elements plus 1 solar radiation scale factor for every hour and 1 y-bias + rate per day.

Table 1 GPS orbit processing summary

In figure 2 are illustrated the comparisons of 8 days (same time-period with our study) of GRGS orbits (using the IGS_01 model) with respect to the IGS final orbits. Helmert transformation was not applied. The total 3d rms agreement (up row) is 7.3 cm. The two red pics in the graphs are satellite PRN24 which is in eclipse. Blue, red and green colours correspond to the Block IIR, Block IIA and Block II respectively. No significant bias (bottom row) is observed in any of the 3 components.

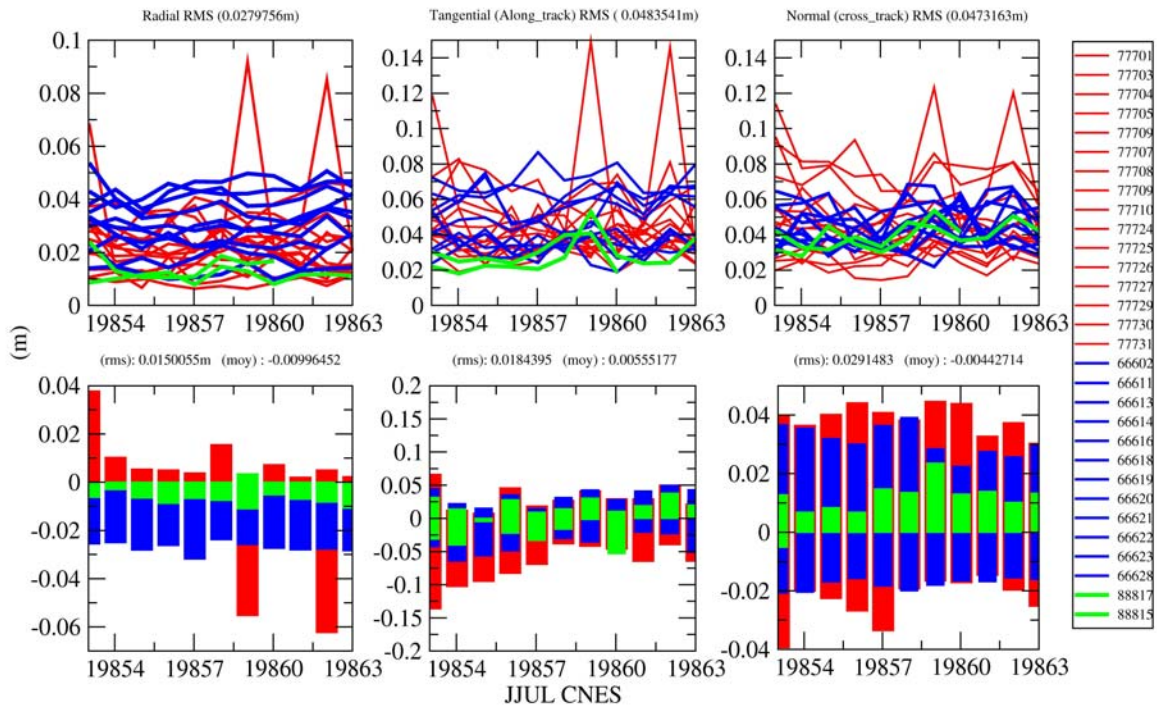

Fig 2. Orbit comparison of GRGS orbits wrt. the IGS final orbits

We did the same comparison, versus IGS combined orbits, with the orbits provided from CODE analysis center in order to verify the quality criterion for the PPP solution. The 3d rms agreement is 2,9 cm. In figure 3 we can see that for the same satellite PRN24 we observe the same two red picks as in the case of our orbits.

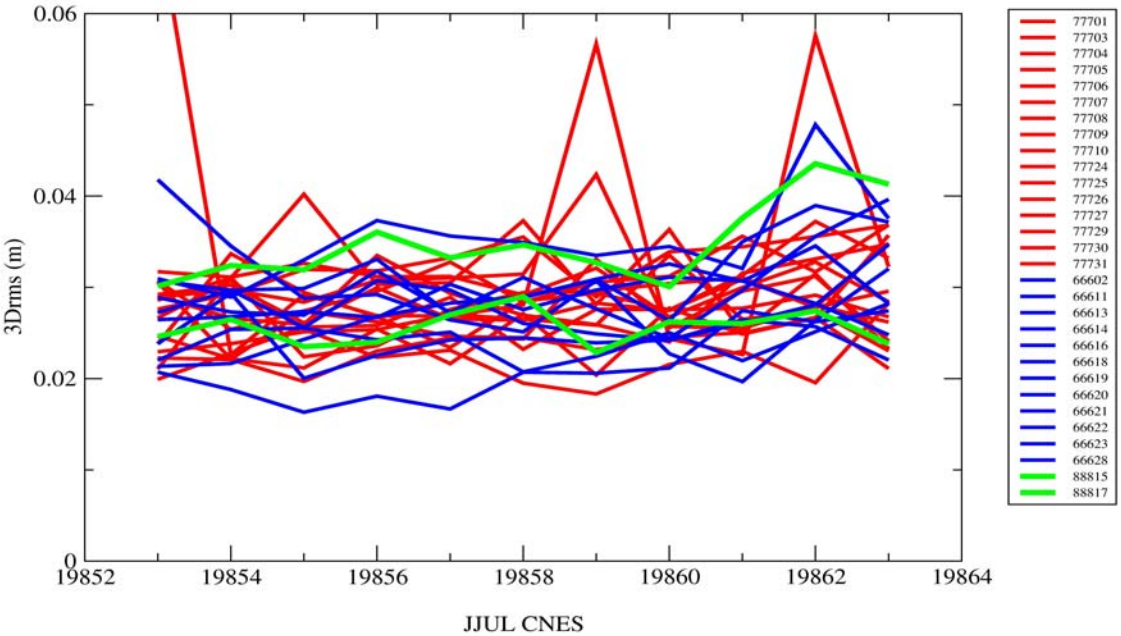

Fig 3. Orbit comparison of CODE orbits wrt. the IGS final orbits

As previously mentioned, ocean loading phenomena have a non negligible impact on the horizontal and vertical components of geodetic stations especially in areas like French Brittany. The high tides in this region provoke an intense loading influence on the crust of N-W France. The amplitudes of the loading signal in terms of vertical displacements, in the stations, can reach up to 10cm peak to peak and some cm in the horizontal components.

We are currently using 8 days of GPS observations and testing seven different analysis strategies in order to quantify the impact of artefacts on the stations time-series and OTL detection. We use a network of 15 EUREF-IGS stations, 5 RGP (Reseaux GPS permanent, Institut Géographique Nationale) stations, and 12 stations from the Brittany campaign. The area of our regional network (Fig.4) is big enough so that the error introduced into station coordinates is comparable to that of a global stabilisation (P. Tregoning, T. van Dam, 2005). We mainly proceed in two steps inside the least squares iteration scheme. Firstly we calculate campaign station positions corrected from every kind of surface deformation (such as atmospheric pressure loading, OTL etc.) in order to have healthy parameters for the ambiguity resolution in the next step. Secondly we calculate time-series of residuals (trend removed and wrt. a mean value) of the campaign stations, without any a-priori corrections due to OTL, in order to study the phenomenon.

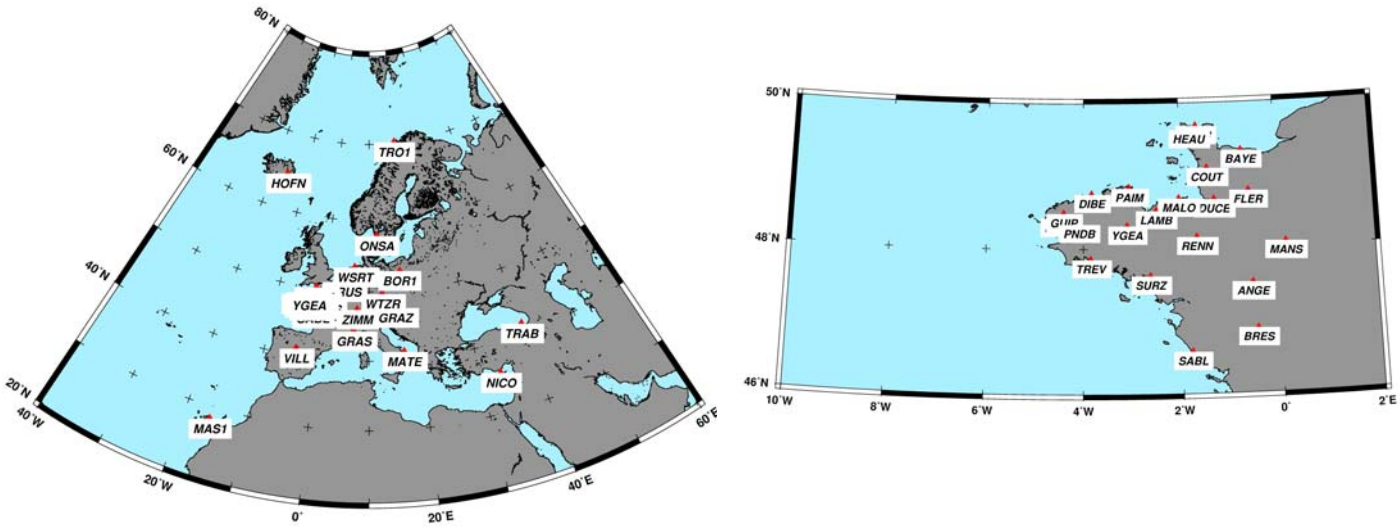

Fig. 4 The regional network and the campaign stations in N-W France

In general we constitute 7 different solutions:

- In solution 1 we use fixed IGS orbits, we do not apply corrections due to antenna phase center variations and we solve for real ambiguity parameters.
- In solutions 2 and 3, we use fixed IGS orbits, we apply relative antenna phase center corrections (IGS_01) and we are either solving or fixing the ambiguities respectively.
- In solutions 4 and 5 we use fixed GRGS orbits, we apply relative antenna phase center corrections (IGS_01) and we are either solving or fixing the ambiguities respectively.
- Solutions 6 and 7 differ from 4 and 5 only to the application of the absolute antenna phase center variations (IGS_05).

The iteration scheme of all strategies contains: IERS earth orientation parameters fixed, corrections for all station positions due to atmospheric loading by using globally gridded ECMWF atmospheric pressure data of 6h (includes atmospheric tides), corrections for solid earth tides according to IERS 2003 conventions, estimations of zenith troposphere delay (ZTD) parameters for every hour, cut-off angle of 10°, production of quasi-observables (partials) for every hour and the constitution of daily normal systems which are cumulated just before the final inversion scheme. The reference frame

stabilisation is realised through the fixed orbits and the constraints of 1mm to all IGS stations. We are applying continuity constraints (coordinate variations) of 1cm per hour to all campaign stations and to all three components. The final solutions consist of estimated relative station positions for every hour. As an example we are analysing the resulted time series of one station "Le DIBEn" (see. above figure). The variation of the relative position and the period spectrum are illustrated in figure 5.

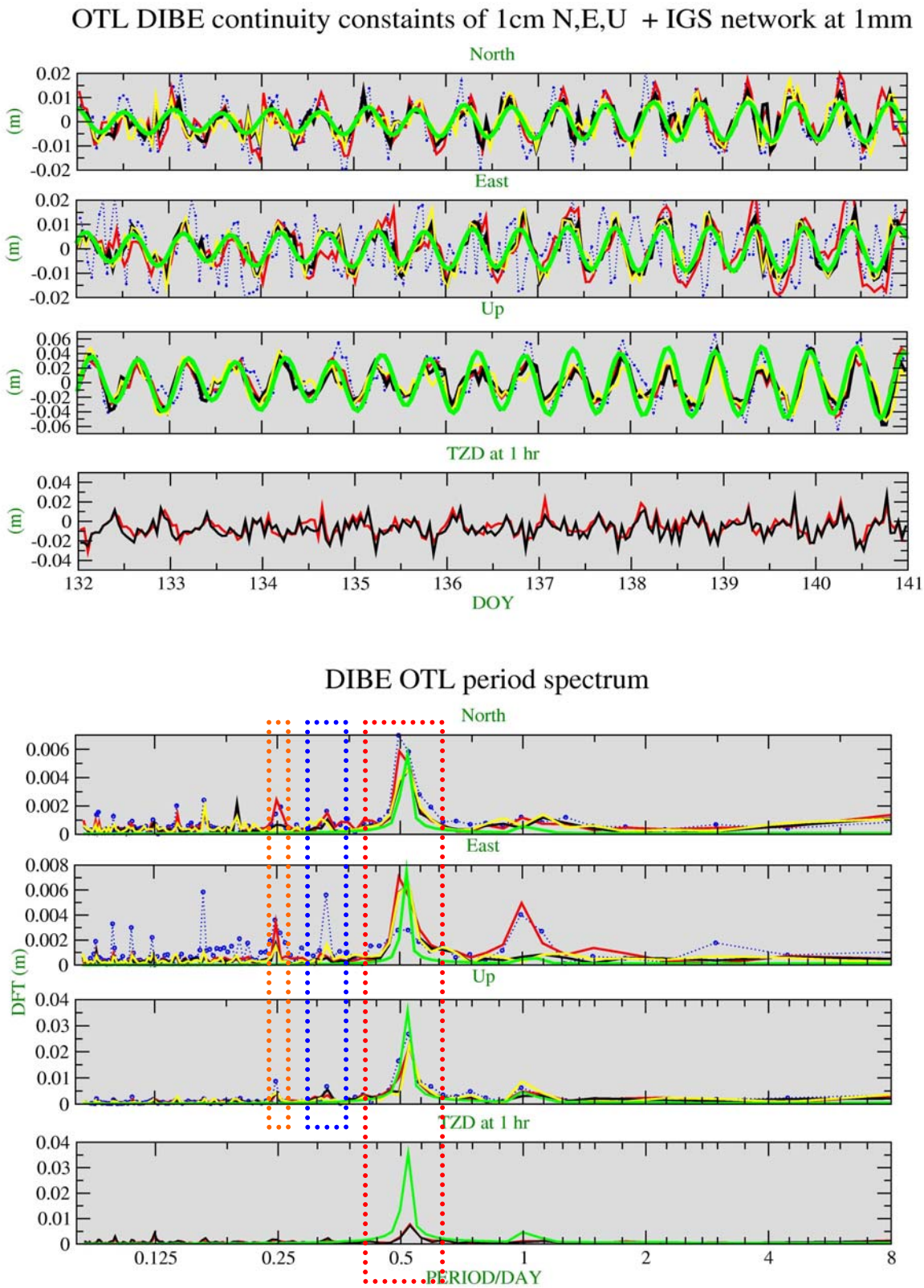

Fig. 5 Time series and spectal analysis for the station "Le DIBEn"

In the above time series in blue is solution 1, in red is solution 2, in black is solution 3, in yellow is solution 7 and in green are the predicted displacements from FES2004. Interesting is the correlation of TZD parameters with the vertical component. From the spectral analysis of the time series it is clear that in all three components the semi-diurnal tides, and especially M2, play the most important role (see red dashed rectangle). Nevertheless, apart from M2, we can obviously detect the ocean loading effect of the M4 tides which exists mainly due to resonance phenomena in the region (see orange dashed rectangle). More peaks reveal a spectral signature around the M3 frequencies (see blue dashed rectangle). Analysis of the other campaign stations is needed.
From a second look, the fact that we used 1hr estimations of TZD does not seem to separate the ocean tide loading and the troposphere effects very well. The signal absorbed by the troposphere parameters, has amplitude of almost 2-4 cm peak to peak, which represents 20-30% of the amplitude of the vertical loading signal. In the next session we are investigating the impact of the different strategies and their relation with the estimated parameters via a regression analysis.

4. Sensitivity analysis and OTL validation

In order to validate the loading model prediction for the "Le DIBEn" station, apart from a first visual analysis of the time series, we examine the correlation coefficients and slopes of a regression analysis of the observed displacements (y-axis) versus the predicted ones (x-axis) from FES2004 model (F. Lyard et al.). In the same time we evaluate the impact of the different solutions to the estimated parameters.
Ocean loading displacements are calculated in the sense of a point-wise loading approach : a gridded surface mass is convolved with Green's functions to determine the load response.
In figure 6.a we can see the regression analysis of solution 1.

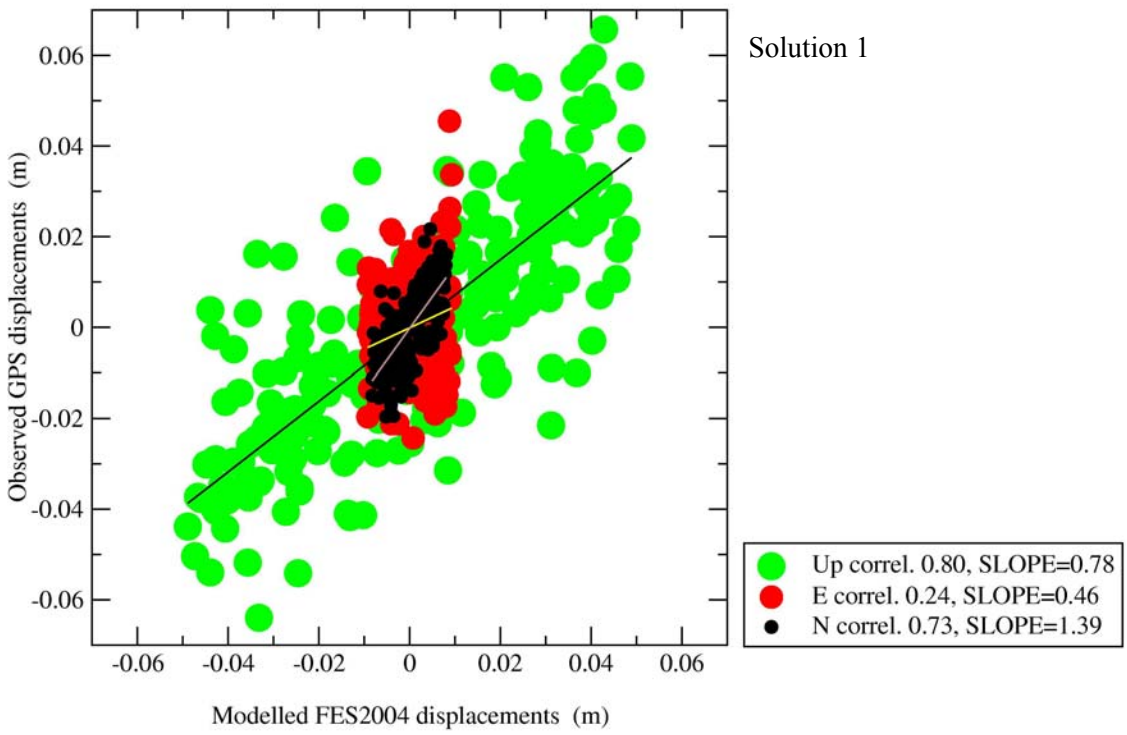

Fig. 6.a

From a first glance we can see that correlations of observed displacement versus predicted, are very poor for the east component. This is, mainly, due to the north-south motion of the GPS satellites at all but high latitudes, where the east component has the highest correlation with the carrier phase

ambiguities. It has been shown that the fixing of ambiguities improves the repeatability of this component more than the others (Melbourne 1985, Blewitt 1989, King et al. 2003).
In order to better understand this artefact as well as the impact of the introduction of the phase center variation maps IGS_01 we have conducted more experiments. In figure 6.b we are illustrating the regression analysis of solutions 2 and 3 (bottom rows) and 4 and 5 (up rows).

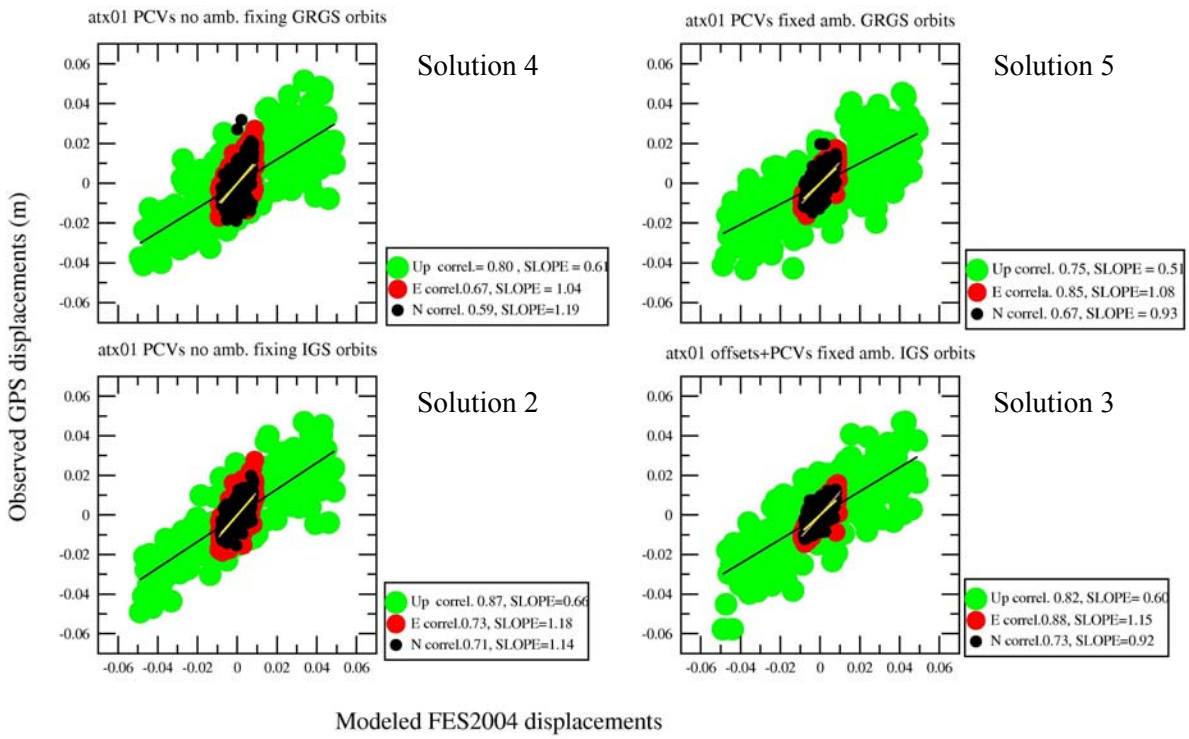

Fig. 6.b

Figure 6.b gives us clearly the image of consistency between the two different frames imposed by the two different orbits. The fact that when ambiguities are fixed (right column) and the correlation in the east component becomes better (88% versus 73% and 85% versus 67%), reflects the improvement in the repeatabilities of the time-series, as previously mentioned. The main reason of this event is that part of the vertical signal is absorbed into the ambiguity parameters whose high correlation with the east component results in the east coordinates being biased with the greatest magnitude (King at al. , 2003). Slope coefficients give us the rate of change in the estimated displacements for a unit change in the predicted displacements. The very smalls differences in terms of slope coefficients between the two different groups of solutions (IGS and GRGS orbits) shows us again the consistency of the two solutions. When it comes to the vertical component, fixing of ambiguities, results in a slope of 0.51 and 0.60, from 0.61 and 0.66 for both groups of solutions (4 and 5, and 2 and 3) respectively. We understand that the slope of the vertical displacements (predicted versus estimated) is worst by a factor of 2 wrt to unity and deteriorates when fixing ambiguities. Though, someone would wait the opposite. Accounting for these scaling factors before and after fixing, we find correlation coefficients of observed and predicted vertical displacements of 80% to 75%, for solutions 4 and 5 (with GRGS orbits), and 87% to 82% for solutions 2 and 3 (with IGS orbits). The agreement in amplitude between the estimated and predicted displacements of the horizontal coefficients is proven by a slope of close to unity. The wrms are Up=19mm, E=6mm, N=6mm in the best case, for solution 5.
In figure 6.c we are comparing the regression analysis of solutions 4 and 5 (up-rows) against 6 and 7 (bottom-rows). We notice immediately that the application of the new standards in solutions 6 and 7, for receiver and satellite antennas, give better correlation coefficients in both cases of ambiguity

resolution. This is obvious for all three components. The vertical component is the one that seems to benefit the most from the new improved antenna conventions (90% correlation versus 81% for ambiguities solved and fixed respectively). Here again there is a small deterioration of the slope coefficients of the modelled and observed vertical displacements, when fixing ambiguities. Exactly the opposite phenomenon happens for the horizontal ones. We can also comment that the scaling factor of the east horizontal component becomes 1.13 from 1.07 after fixing ambiguities. This verifies our statement that there is more signal contained in the estimated time series than those modelled. This is also obvious in the spectral analysis conducted further up (Fig. 5), as well as that part of the amplitude of the vertical signal is absorbed into the tropospheric parameters. Previous studies from Santerre (1991), S. Vey et al. (2002), C. Urschl et al. (2005), reveal that there is a strong mitigation of the loading signal in the ZTD. The horizontal components are not correlated with the troposphere. But, since the absorption of part of the vertical signal passes from the ambiguity parameters to the east component, it seems that fixing of ambiguities helps the mitigation of part of the vertical signal to the troposphere parameters as well. More investigation is needed in terms of correlation coefficients between ZTD parameters and observed vertical displacements. The wrms are Up=20mm, E=7mm, N=7mm in the best case, for solution 7.

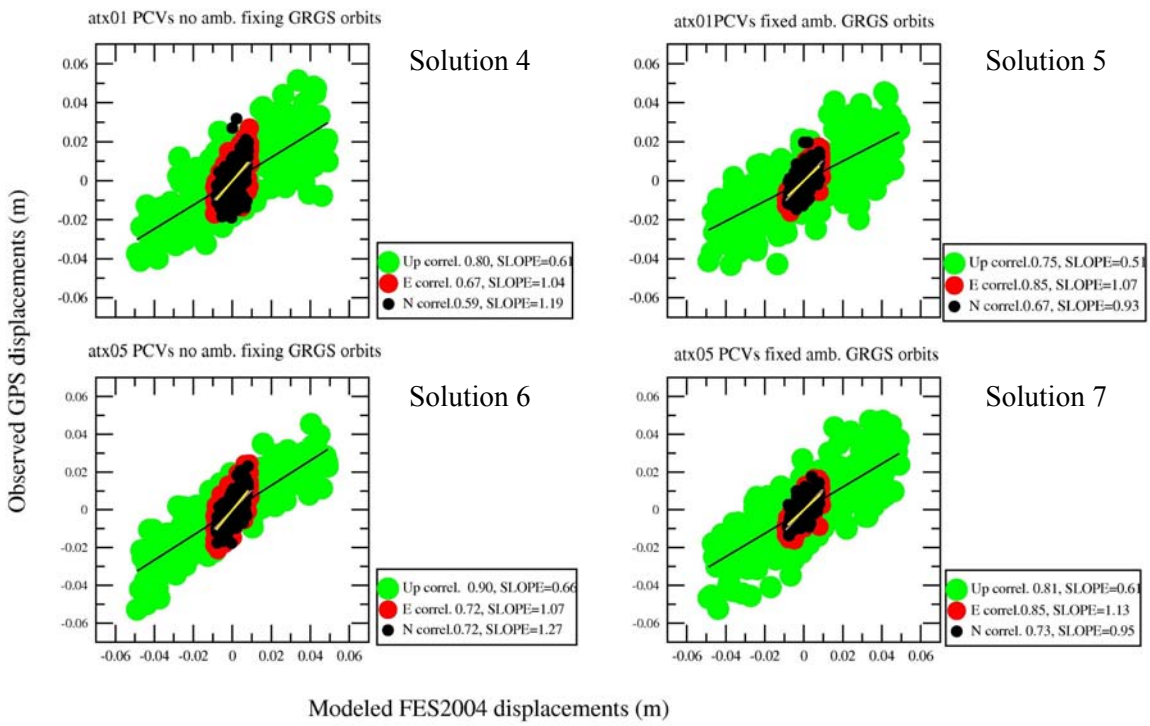

Fig. 6.c

Although, we have to mention that our troposphere modelling is based on a simple mapping function. S.A. Khan and H.G. Scherneck (2003) have shown that independent 1hr solutions should give troposphere parameters de-correlated from biases. Our solutions come from 1-d intervals, but we are estimating station positions together with troposphere parameters for every hour. Then again if we follow the strategy of S.A. Khan and H.G. Scherneck (2003), by applying independent 1hr solutions, we are risking having ambiguities not accurately fixed and introduce artefacts in the East component.

5. *Precise Point Positioning processing*

In order to quantify the differences of an absolute positioning method with respect to the relative double differences strategy, we have conducted a Precise Point Positionning solution using the CODE orbits and the CODE 30 sec GPS clock products. Results for the same station are illustrated in figure 7. In blue line are the estimated values and in green the predicted ones. For reasons of quality checking we have plotted in the same picture the comparison between the final IGS 15min clocks and the 30s CODE clocks for doy 132 of 2004 (beginning of our experiment).

The strategy used for the same station "Le DIBEn" is: CODE orbits and clocks fixed, 1day sessions with partials created for every 1-hr, ZTD parameters are estimated for every 1hr, cut-off angle 10°, we correct for all displacements due to solid tides and atmospheric loading, we use the IGS_01 standards for receiver and satellite antennas, ambiguities are solved and station clocks are estimated, we apply continuity constraints of 0.4cm/hr to the N, E and 1cm/hr to the Up components. First thing we can observe is that repeatabilities are of worst quality than the ones from the double differences approach. Secondly the spectral analysis reveals signals of higher frequencies that do not have realistic amplitudes. Troposphere parameters seem to absorb a big part of the vertical signal in all frequencies which was not the case for the double difference approach. Thirdly, from the regression analysis, correlation coefficients are very poor, especially for horizontal components.

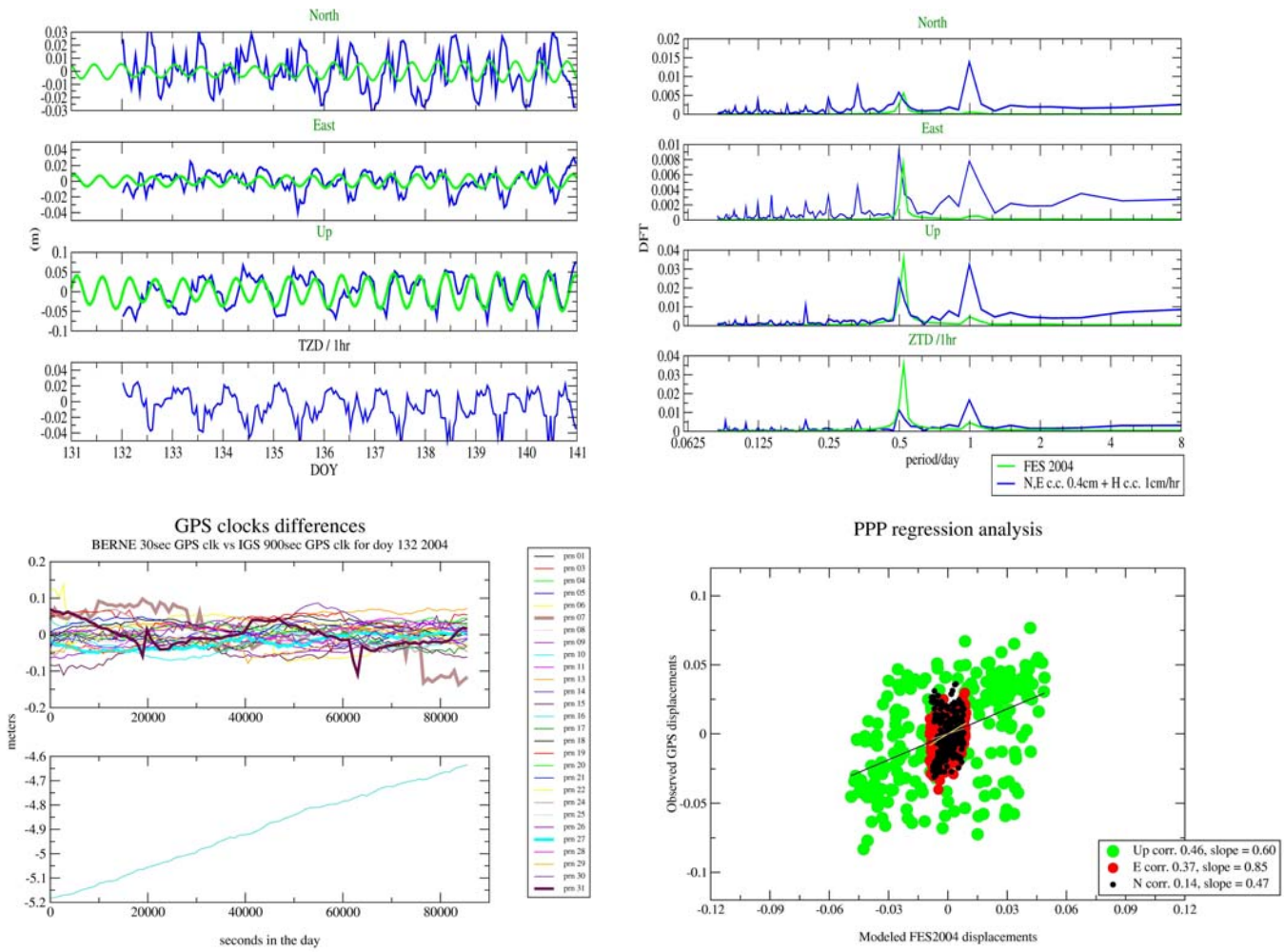

Fig. 7. PPP analysis results for the station "Le DIBEn"

6. Conclusions

We are validating our GPS orbits by comparing with the ones of IGS for the relative antenna calibration model case. In a second phase, we are applying the IGS_05 absolute antenna calibration model and we are re-estimating GPS orbits for the same time period. In a third phase we compare two regional networks solutions in which we understand that when fixing our orbits estimated with IGS_01 standards the results are consistent with the solution in which we fix the IGS orbits (estimated as well with the IGS_01 standards). In a forth phase we make internal comparisons of the regional networks solutions in where we fix our two kinds of GPS orbits in order to evaluate the differences between the two antenna calibration standards in the hourly estimated station positions. We finally conclude that the new calibration standards IGS_05 for receiver and satellite antennas give the best internal consistency in terms of correlation and slope coefficients of the campaign station positions as a result of noise reduction and artefacts in the final time-series. This is particularly obvious in the vertical component when compared to the OTL FES2004 model (see Fig. 6.c.).

Previous studies of ocean loading in the region of French Brittany (S. Vey et al. 2002, M. Llubes et al. 2001) and other parts of the globe (King et al. 2003, A.S. Khan and H.-G. Scherneck 2003) have given validation OTL modelling results, as far as it concerns the linear part of ocean tides. We are proposing a new validation method for ocean loading deformation which includes displacements due to the non linear spectrum of tides (M3, M4, M6, etc). The amplitudes of these can reach up to 1cm and even more, mainly because they are strongly depending from the ocean bottom morphology of the region. For high precision geodetic applications it is an absolute need to correct for these phenomena especially in coastal areas. Another conclusion that comes from the regression analysis of slope coefficients is that, in all cases, we observe more signal amplitude in the estimated horizontal components than in the predicted ones. This agrees very well with the fact that our analysis detects the loading influences of the non linear tides that are not included in the model.

Ambiguity fixing liberates the east component from vertical biases transferred in the real ambiguity unknowns. One important conclusion of the regression analysis is that the observed vertical signals seem to have slightly smaller amplitudes than the ones modelled, especially after fixing ambiguities (see Fig.6.b and Fig.6.c). Accounting for the resulted scaling factors the correlation coefficients between vertical estimated parameters and the predicted ones, become worst. This verifies our suspicions that the troposphere parameters are responsible for the loss of about 20-30% of the vertical loading amplitude. This becomes more obvious after eliminating one of the sources of vertical signal absorption like the ambiguity parameters. From the other hand, 1hr independent solutions could have given uncorrelated troposphere parameters but they can lead to the erroneous fixing of ambiguities (due to the short time-length of 1hr) and biasing of the east horizontal component. Moreover, the poor troposphere modelling needs to be improved. For that a new mapping function of Marini type with calculation of horizontal gradients and a-priori troposphere model for the dry and wet component from ECMWF 6h field is on the way.

The Precise Point Positioning approach did not give comparable results to the double difference strategy but more work is in progress. That of course does not come to question the PPP principle but only our implementation strategy.

The choice of the analysis strategy plays a very important role in the final interpretation of OTL results.

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