The Effect of Processing Technique and Reference Frame Definition on Noise in CGPS Position Time Series

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Abstract

In this presentation we investigate the effects of GPS processing techniques and strategies, and the related reference frame realization, on the stochastic properties of continuous GPS (CGPS) position time series. It was of particular interest to establish whether and how different GPS processing techniques and strategies, e.g. double differencing (DD) and precise point positioning (PPP), and the use of different orbit and clock products, and/or the definition of the reference frame (partly dependent on the applied strategy) affect the colored noise content of time series. We used CGPS position time series from 15 different solutions obtained from seven different analysis centers as part of the European Sea Level Service - Research Infrastructure project (ESEAS-RI) using the GIPSY OASIS II, GAMIT and Bernese GPS softwares. All time series analyzed have at least three years of data for the period between 2000 and 2005. Furthermore, a selected set of position time series was also analyzed using Empirical Orthogonal Function (EOF) analysis. The noise content of the first 15 modes, representing the solution-specific common mode time series for each of the selected solutions were then also investigated for colored noise. Using Maximum Likelihood Estimation (MLE) a white, a white plus flicker, a white plus power-law and a white plus first-order Gauss-Markov (FOGM) noise model were fitted to the position and EOF time series data. For both the position and EOF time series the parameter model included a constant, a rate and harmonic terms with annual, semi-annual, 4-monthly, 3-monthly, 2.4-monthly and 13.66 day periods. Position jumps were modeled at logged epochs or at visible discontinuities in the time series. The MLE showed that in most cases the best fitting noise model is a combination of white plus power-law noise with average spectral indices in the range between -0.5 and -1.4. This model is closely followed by the combination of white plus flicker and white plus FOGM noise. The noise properties of the EOF time series follow predominantly a white plus power-law character, with the first few modes indicating a white plus flicker noise behavior. In general, DD solutions contain less noise than PPP solutions and that regional reference frame definitions further reduce the amount of noise in the time series.

Introduction

Continuing the work of *Williams et al.* [2004], the authors investigated the effect of different GPS processing techniques, strategies and reference frame definitions on stochastic noise in CGPS coordinate time series. The time series stem from ~30 CGPS stations located at or close to tide gauges in Europe (Figure 1), for which data have been processed by seven different analysis centres. These include six analysis centres of the European Sea Level Service Research Infrastructure (ESEAS-RI) project and one of the IGS Tide Gauge Benchmark Monitoring Pilot Project (TIGA-PP) (Table 1). Table 2 shows the relevant details of the CGPS coordinate time series used by the authors from each analysis centre.

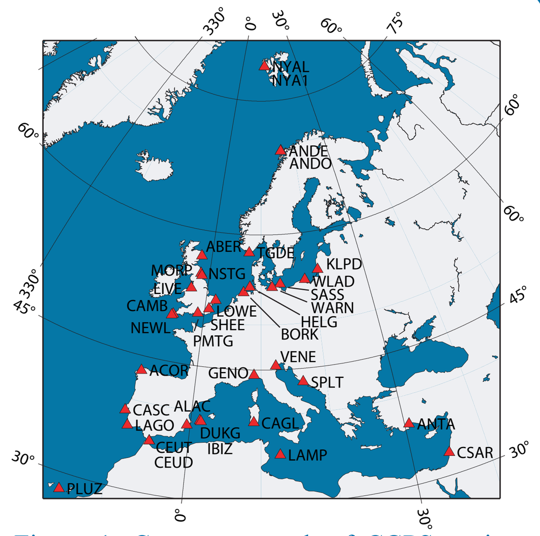

Figure 1: Current network of CGPS stations processed by the six ESEAS-RI CGPS ACs.

Table 1: Analysis centres for which CGPS coordinate time series have been analyzed.

Analysis Centre	Abbreviation	Affiliation
General Command of Mapping, Ankara, Turkey	GCM	ESEAS-RI
Norwegian Mapping Authority, Honefoss, Norway	NMA	ESEAS-RI
Royal Naval Observatory of Spain, Cadiz, Spain	ROA	ESEAS-RI
Space Research Center, Warszawa, Poland	SRC	ESEAS-RI
University of La Rochelle, La Rochelle, France	ULR	IGS TIGA PP
University of Nottingham, Nottingham, United Kingdom	UNOTT	ESEAS-RI
Universidad Politécnica de Cataluña, Barcelona, Spain	UPC	ESEAS-RI

Table 2: Solution Matrix of the CGPS coordinate time series analyzed by the authors. The table shows long and short solution abrreviations, the reference frame of the time series, the GPS software used, the processing technique and strategy used, and additional comments. Detailed information on the GPS processing can be obtained from *Kierulf et al.* [2005].

Analysis Centre	Solution (long)	Solution (2-char)	Reference Frame	Software	Technique	Strategy (orbits & clocks)	Comments
GCM	gcm_gns	gg	global/ITRF2000	GAMIT/GLOBK	DD	IGS	
	gcm_rns	gr	regional/ITRF2000	GAMIT/GLOBK	DD	IGS	
NMA	nma_igs	ni	global/IGb00	GIPSY OASIS II	PPP	IGS	
	nma_jpl	nj	global/ITRF2000	GIPSY OASIS II	PPP	JPL/x-files	2 extra offsets in 2004
	nma_jpln	n1	global/ITRF2000	GIPSY OASIS II	PPP	JPL/x-files	1 extra offset in 2004
ROA	roa	rg	global/ITRF2000	GIPSY OASIS II	PPP	JPL/x-files	2 extra offsets in 2004
	roa_jpln	r1	global/ITRF2000	GIPSY OASIS II	PPP	JPL/x-files	1 extra offset in 2004
SRC	src	sr	regional/ITRF2000/wtzr	Bernese v4.2	DD	IGS	only up to October 2004
	src_it00x	sx	global/ITRF2000	Bernese v4.2	DD	IGS	
	src_ig00x	n/a	global/IGS00	Bernese v4.2	DD	IGS	
ULR(TIGA)	ulr	n/a	global/ITRF2000	GAMIT/CATREF	DD	IGS	some station overlap, different time spans and gaps in time series
UNOTT	unott_eg7p	ug	global/ITRF2000	Bernese v5.0	PPP	IGS	
	unott_er4p	ur	regional/ITRF2000	Bernese v5.0	PPP	IGS	
UPC	upc	uc	global/ITRF2000	GIPSY OASIS II	PPP	JPL/x-files	only up to October 2004 2 extra offsets in 2004
	upc_jpln	u1	global/ITRF2000	GIPSY OASIS II	PPP	JPL/x-files	only up to October 2004 1 extra offset in 2004

CGPS Coordinate Time Series Analysis Strategy

The authors applied a coordinate time series analysis strategy primarily designed to obtain highly accurate station velocity estimates with realistic uncertainties, i.e. by accounting for coloured noise in the CGPS coordinate time series [*Teferle et al.*, 2005]. However, through a combination of the main analysis methods, Maximum Likelihood Estimation (MLE) and Empirical Orthogonal Function (EOF) analysis, it is possible to improve the understanding of CGPS coordinate time series and their stochastic properties.

The CGPS coordinate time series analysis strategy incorporates both a pre-processing and an actual coordinate time series analysis stage. During the pre-processing stage several tasks are carried out:

- Detection and removal of outliers
- Detection and removal of periods of "bad" data
- Detection of significant periodic signals
- Detection and validation of coordinate offsets

In the coordinate time series analysis stage the authors use the MLE to estimate the slope and intercept, annual, 6-, 4-, 3- and 2.4-monthly, and 13.66 day signals, and coordinate offset magnitudes at any known or required epochs. Furthermore, the authors evaluated four different stochastic noise models:

- White noise (WN)
- White plus power-law noise (WN+PLN)
- White plus flicker noise (WN+FN); special case of WN+PLN
- White plus First-order Gauss-Markov noise (GM)

The EOF analysis of the CGPS coordinate time series provides a description of the spatial and temporal variability of the time series, and can be used to quantify common systematic variations observed for a specific solution. These coomon mode signals often depend on the CGPS processing technique and strategy, and the reference frame realization. In order to characterize the stochastic noise of these common modes, the authors analyzed the EOF time series using MLE.

Figure 2 gives a schematic overview of the coordinate time series analysis stage.

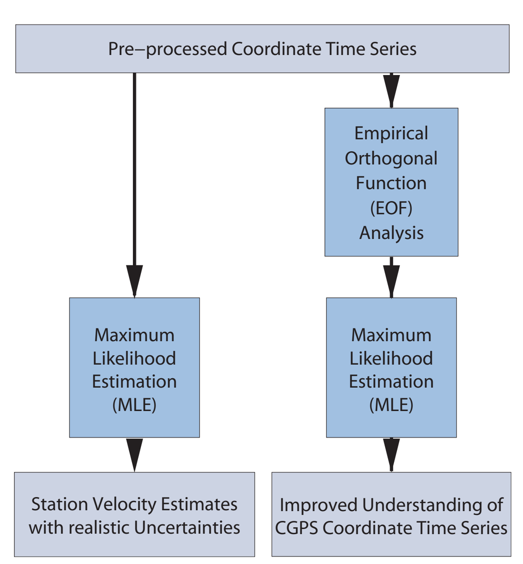

Figure 2: Schematic of the coordinate time series analysis stage. The pre-processed coordinate time series are analyzed in multiple ways to infer a set of station velocity estimates with associated uncertainties. The EOF analysis and the following MLE of the "common modes" improves the understanding of the common systematic variations in the CGPS coordinate time series.

Results: CGPS Coordinate Time Series

The authors have analyzed 15 different CGPS coordinate time series solutions (Table 2). Figure 3 shows the height time series for Newlyn for ten selected solutions.

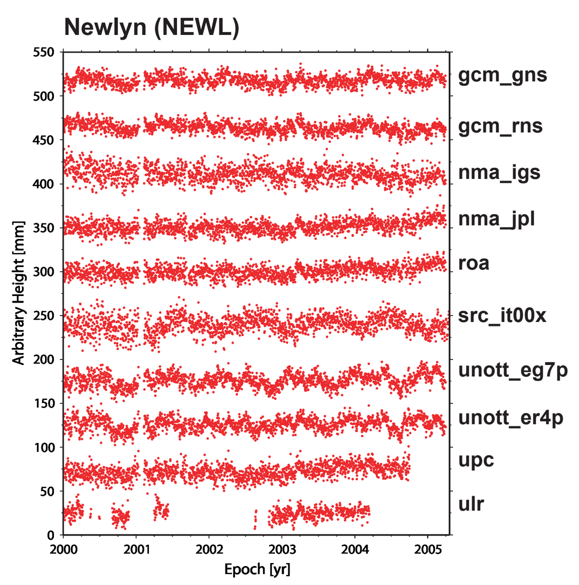

Figure 3: Height time series for Newlyn for ten different coordinate time series solutions. Clearly visible are the different characteristics of the time series depending on processing technique and strategy, and reference frame definition. The height time series show good agreements for solutions nma_jpl, roa and upc. The height time series of solutions nma_jpln, roa_jpln and upc_jpln are not displayed as these are equivalent to nma_jpl, roa and upc, respectively, and only differ in their modelling. The time series of solution src and src_ig00x are not shown as these are very similar to src_it00x.

Results: Identification of the Best Noise Model

Four noise models have been fitted to the coordinate time series for each of the 15 solutions. For all solutions a white plus coloured noise model is preferred over the white only noise model (Figure 4). The identification of a best coloured noise model cannot be based on the MLE values only, as these, e.g. in the presence of WN+FN, tend to be slightly larger for the WN+GM and WN+PLN models than for the WN+FN model. An alternative method to differentiate between these models is demonstrated (Figures 5 and 6).

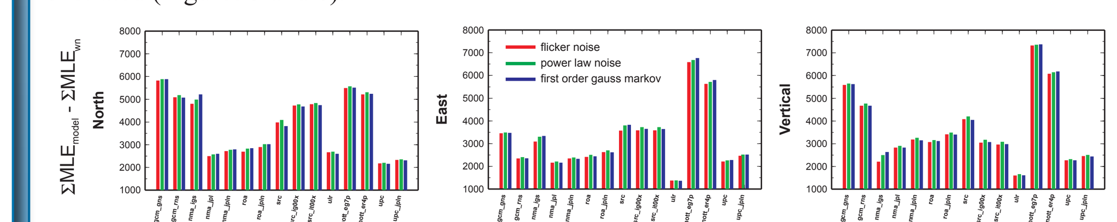

Figure 4: Differences of the sum of the MLE values for each coloured noise and the white only noise model per solution. Most differences for the coloured noise models are insignificant, thus do not alone allow an identification of a best coloured noise model.

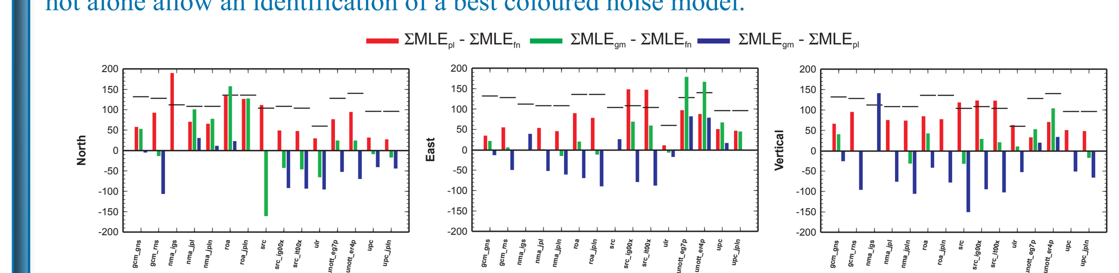

Figure 5: Significance tests for different coloured noise models per solutions. In most cases the hypothesis of WN+PLN and WN+GM can be rejected in favour of the null hypothesis of WN+FN being the best representation of the noise. In other words, although the differences ΣMLE_{pl}-ΣMLE_{fn} are positive, they are not positive enough to be significant (see also Figure 7). Significance threshold is indicated by horizontal lines.

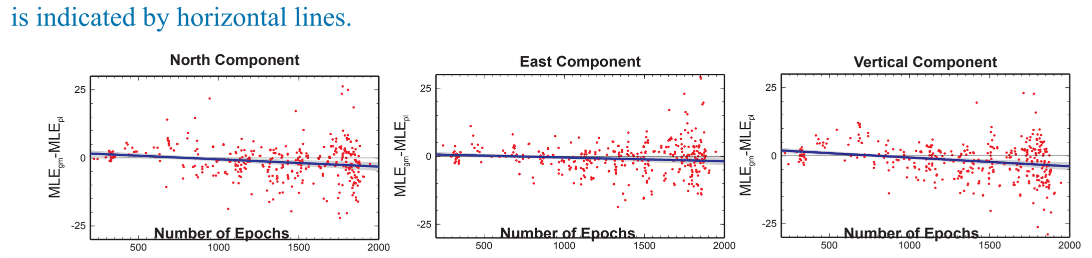

Figure 6: Differences of MLE values for the WN+GM and WN+PLN models per number of observation epochs in the time series. As the number of epochs increases, the differences become more negative, indicating that despite the fact that the differences are more positive for a smaller number of epochs, the MLE is starting to distinguish correctly, in favour of WN+PLN, between the two noise models. The line is a fit to the differences. The error boundaries are 1σ.

Results: Spectral Index Estimates

The spectral index estimates from the MLE (WN+PLN) have been evaluated for their stability (Figure 7) and their solution-dependency (Figure 8).

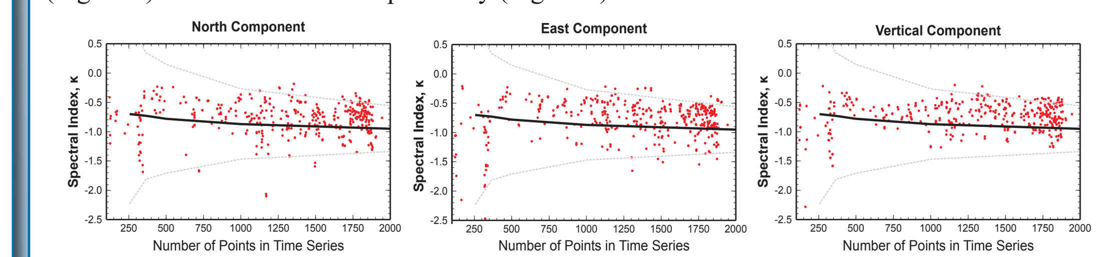

Figure 7: Spectral indices per number of points in the coordinate time series from MLE (WN+PLN). Thick black line shows theoretical index derived from simulated WN+FN data [*Williams et al.*, 2004]. Error bounds are 3σ.

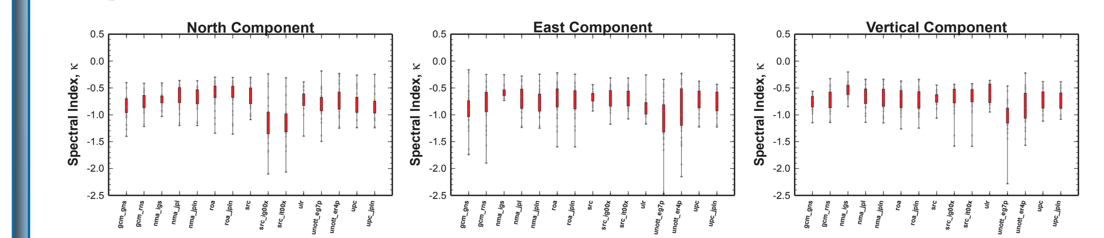

Figure 8: Stem & Box plots of spectral indices per solution. The spectral indices generally fall between -0.5 and -1.4. There is some indication of a solution-dependency of the indices, especially for the solutions unott_eg7p and unott_er4p.

Results: Noise Amplitude Estimates

Figures 9 and 10 show the white and flicker noise amplitudes from the MLE (WN+FN). Clearly, the effect of different CGPS processing techniques and strategies, and reference frame realizations is visible. Interestingly, also the ratio of the white and flicker noise amplitudes show signs of solution-dependency (Figure 11). Finally, a ranking of the different solutions is given (Table 3).

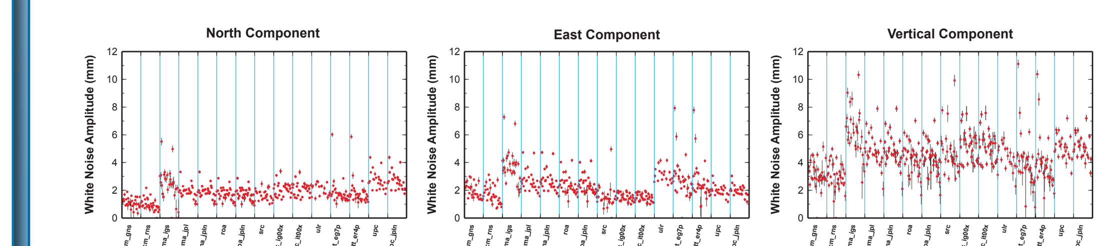

Figure 9: White noise amplitudes from MLE (WN+FN) per solution. Error bars are 1σ.

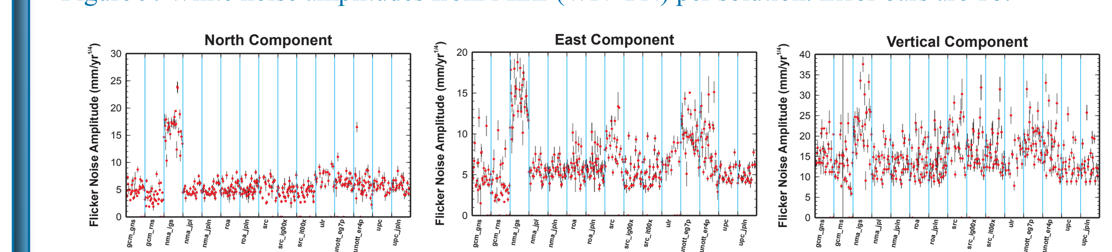

Figure 10: Flicker noise amplitudes from MLE (WN+FN) per solution. Error bars are 1σ.

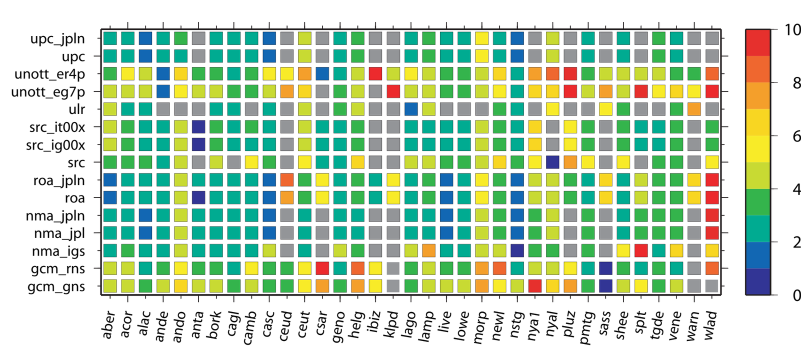

Figure 11: Ratio of flicker and white noise amplitudes from MLE (WN+FN) per solution and station. Gray squares indicate that no values are available (N/A).

Table 3: Ranking of solutions depending on noise amplitudes. Table shows mean noise amplitudes and ranking in brackets.

Solution	White Noise [mm]						Flicker Noise [mm/yr^1/4]					
	North		East		Height		North		East		Height	
gcm_rns	0.4	(1)	0.9	(3)	1.7	(1)	1.8	(1)	1.4	(1)	7.5	(1)
gcm_gns	0.6	(2)	1.2	(5)	1.8	(2)	2.8	(4)	2.9	(2)	10.3	(8)
src_it00x	1.3	(8)	0.8	(1)	3.7	(11)	2.1	(2)	3.2	(3)	11.2	(10)
src	1.0	(3)	1.0	(4)	3.1	(5)	2.9	(5)	5.9	(12)	13.0	(13)
src_ig00x	1.3	(9)	0.8	(2)	3.7	(14)	2.2	(3)	3.2	(4)	11.4	(11)
roa	1.3	(7)	1.8	(9)	3.3	(7)	3.6	(8)	4.0	(9)	9.2	(4)
roa_jpln	1.3	(6)	1.8	(8)	3.3	(8)	3.7	(9)	4.0	(10)	9.4	(5)
nma_jpl	1.4	(10)	1.9	(12)	3.5	(9)	3.1	(6)	3.7	(7)	9.5	(6)
upc	2.0	(14)	1.3	(7)	3.7	(13)	3.7	(10)	3.4	(5)	9.1	(2)
upc_jpln	2.0	(13)	1.3	(6)	3.7	(12)	3.7	(11)	3.4	(6)	9.2	(3)
nma_jpln	1.4	(11)	1.9	(11)	3.5	(10)	3.1	(7)	3.8	(8)	9.5	(7)
unott_er4p	1.2	(4)	1.8	(10)	2.5	(3)	4.0	(12)	6.1	(13)	11.9	(12)
unott_eg7p	1.2	(5)	2.0	(13)	2.8	(4)	4.5	(13)	8.1	(14)	14.3	(14)
ulr	1.6	(12)	2.5	(14)	3.2	(6)	5.8	(14)	4.7	(11)	10.8	(9)
nma_igs	2.1	(15)	3.2	(15)	5.1	(15)	14.8	(15)	12.7	(15)	18.2	(15)

Results: MLE of the EOF Analysis Results

Four noise models have been fitted to the EOF time series for each of the 15 solutions. The differences of the MLE values for the coloured noise models indicate a preference of WN+PLN over WN+FN. For most solutions and EOF modes, the WN+PLN model does, however, not fit significantly better than the WN+FN model (Figure 12). The spectral index estimates from the MLE(WN+PLN) mostly vary between -0.2 and -1.4 with few outliers, and show differences between solutions and EOF modes (Figure 13). A whitening with increased EOF mode is visible with a jump to more coloured noise at EOF modes 11 and 12 (Figure 13b). Flicker and white noise amplitudes have been obtained from the MLE(WN+FN). A strong decrease of flicker noise with increasing EOF mode is indicated (Figure 14a). The decrease of white noise with increasing EOF mode (Figure 14b) is less dramatic than for flicker noise. The white noise component of the first EOF mode seems bi-modal in nature, indicating common white noise that is exactly the same at all stations of a specific solutions, which is coupled with white noise that varies at each station. In contrast, flicker noise indicates a spatially correlated signal.

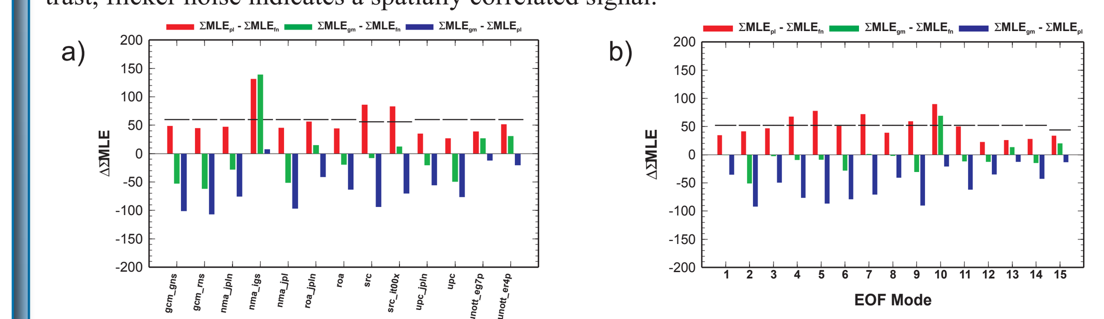

Figure 12: Significance tests for different coloured noise models per solution (a) and EOF mode (b). Test of the hypothesis of WN+PLN and WN+GM against the null hypothesis of WN+FN. See Figure 5 for further explanation. Significance threshold is indicated by horizontal lines.

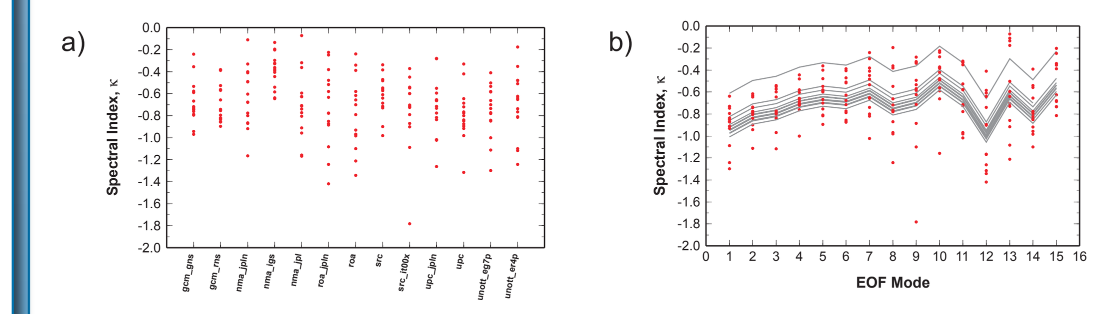

Figure 13: Spectral index estimates for EOF time series from MLE (WN+PLN) per solution (a) and EOF mode (b). Gray lines in (b) indicate spectral indices per solution.

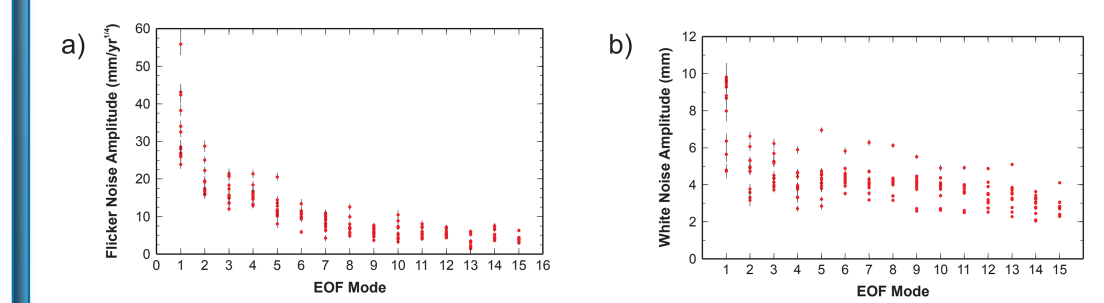

Figure 14: Flicker (a) and white (b) noise amplitudes for EOF time series from MLE (WN+FN) per EOF mode.

Conclusions

The coordinate time series for ~30 CGPS stations from 7 analysis centres and 15 different solutions have been analyzed using MLE and EOF analysis with respect to the effects of CGPS processing technique and strategy, and reference frame realization.

The main findings are:

- The white plus power-law noise (WN+PLN) and white plus flicker noise (WN+FN) models were identified as best representation of the stochastic properties for most coordinate and EOF time series. Although, the MLE values favoured WN+PLN over WN+FN, WN+FN cannot be ruled out.
- Spectral indices and noise amplitudes for coordinate and EOF time series differ per solution and EOF mode and are generally in the range between -0.5 and -1.4 for coordinate time series and -0.2 to -1.4 for EOF time series.
- Ratio of flicker and white noise shows large variations per solution.
- The ranking of the solutions shows that regional solutions are less noisy than global solutions and that double difference solutions are less noisy than precise point positioning solutions.
- The regional GAMIT/GLOBK (gcm_rns) and the global GIPSY OASIS II (nma_igs) solution were identified as best and worst solutions, respectively. It should be noted that the increased amount of noise in this solution can be entirely explained by the use and the nature of IGS final products within GIPSY OASIS II.
- The amount of noise in the EOF time series decreases and becomes whiter with increasing modes. There is an indication that the white noise component of the first mode is bi-modal in nature.

Further research on potentially larger data sets is required in order to reduce site-specific effects.

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