Acknowledgement

- ❑ **IAG + UP+CSIR**

  Made available funds to attend the 1st IVS General Meeting

- ❑ Some person(s) who introduced me to Space Geodesy
  - R. Haas (Chalmers University)

    Scientific definition of Space Geodesy
  - Vienna group (Schuh & Boehm)

    Instilled confidence in the analysis of Space Geodesy data

Local oscillatory signals in geodetic tropospheric delay

[1] Botai O. J., [1 3] Combrinck L. W. [1 2] Sivakumar V., [1] Rautenbach C. J., [4] Schuh H., and [4] Boehm J.

[1] University of Pretoria

[2]CSIR-South Africa

[3] HartRAO

[4]Vienna Technical University

Contents

❑ Introduction

- Long history of geodetic data

❑ Data and Method

- Data
- Method [Empirical Mode Decomposition (EMD), Independent Component Analysis (ICA) & Phase synchronization]

❑ Test Results

- Intrinsic Mode Functions (IMFs)
- Independent Components (ICs)
- Phase synchronization

❑ Summary

Long history of geodetic data

- VLBI observations (e.g., since Jan 1979)
- GPS observations (since Jan 2005)
- SLR measurements
- Geodetic products: EOP, LoD, dUT1, station coordinates
- Working dictum:

  "the derived geodetic data has the required scientific accuracy"

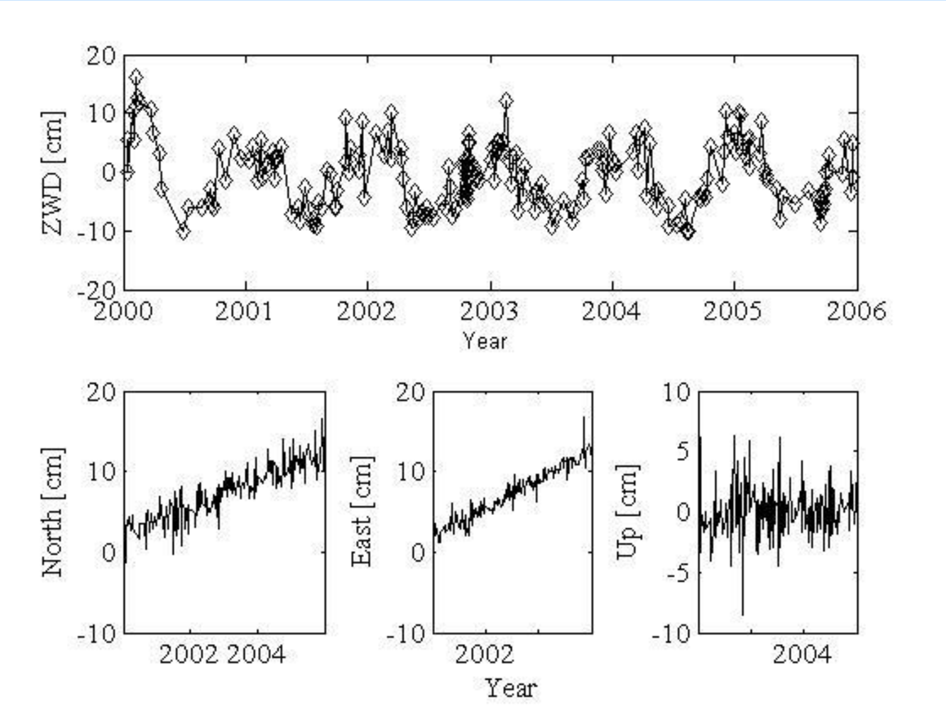

Figure 1. ZWD and NEU at HartRAO between 2000 and 2005. Data source [1].

Post -analysis of these data

- **Some of the reported analysis strategies in the literature**
  - Bengtsson et al, (2004):-A global deterministic component of **+0.36 kg m $^{-2}$** per decade of IWV from ECMWF 40-year reanalysis data
  - Jin et al., (2007):- used ZTD derived from GPS and computed a linear trend of **15 mm per decade**. These results also showed regional dependence
  - Nilsson & Elgered, (2008):- used data from ground-based GPS and computed long-term linear trends ~0.2 -1.0 kg m $^{-2}$
  - In all these studies, a functional form of the trend is subjectively determined i.e. **the function that represent the trend is pre-selected**
  - Are there no tractable & a robust way to decipher components in the data? **Data adaptive methods exist** e.g., Zhauhua et al., (2007)

Post -analysis of these data

❑ Post-analysis strategies: a new direction

- ➢ Look at the series as a mixture of components e.g.,
- trend (a slowly evolving component that have a global span) & other quasi-periodic components & a noise component.
- Assume that these components are additive and fluctuate at different timescales.
- Extract components embedded in the data by use of nonparametric methods e.g. Empirical mode decomposition [2], Wavelets [4], Independent Component analysis [3]

Post -analysis of these data

❑ Post-analysis strategies: a new direction

- Use a combined EMD-ICA algorithm to extract local oscillatory components.
- In this regard, the ZTD observations could be modeled as:

$$y_j(t) = \sum_{i=1}^{N} \beta_{i,j} s_i(t)$$

- Here, *s* are the signals components , *y* represent the measurement and j spans over the observation space.

Post -analysis of these data

❑ Post-analysis strategies: a new direction

- In matrix formulation, Y is the matrix of observations, S a matrix of underlying signals and noise (could Gaussian) , observation model can be expressed as

$$Y=AS+\delta$$

- Then, determine whether the signal components have any linkage with known geophysical signals by calculating the synchronization index, see for example [5]

Data & method

- ☐ Six IVS stations: data span of ~ 11 years

IVS station Name	Daily data records
HartRAO	4191
Hobart26	4191
Wettzell	4191
Westford	4191
Gilcreek	4191
Sukub32	4183

Data & method

- ❑ Other geophysical signals (monthly anomalies)
  - Quasi-Biennial Oscillation (QBO) derived from NCEP/NCAR reanalysis
  - Southern Oscillation Index (SOI) from NCEP
  - Sun Spot Number (SSN) available at www.sidc.oma.be
  - Length of Day (LoD); an IERS product

Method

- ☐ Extracting oscillatory components: EMD-ICA algorithm

1. Add iid white noise (with zero-mean and $\sigma_{iid}=\lambda\sigma_0$) to ZTD. Here the noise parameter λ is arbitrary taken as 0.3
2. EEMD [2] to extract a set of ZTD IMFs.
3. Determine the Independent components using FastICA[3] on the IMFs obtained in 2.

ICA model & clustering

- Simple linear model of the form

$$\mathbf{x} = \mathbf{A}\mathbf{s}$$

- Here, **A** is the mixing matrix, **s** are the independent sources and **x** are signal components in the series. In practice, what is estimated in the inverse of pseudo inverse (also called the de-mixing matrix) such that

$$\mathbf{s} = \mathbf{W}\mathbf{x}$$

Clustering

- For a data matrix: $\mathbf{X = [x_1\ x_2\ \text{- - -}\ x_N]}$

  Here, N is the number of signal components (IMFs) with a total temporal span of K. Now run M times (with a selected criteria for initial conditions e.g., bootstrapping or randomizing or a combination of both [3]) to obtain

$$W=[W_i^T]^T \qquad i=1, 2, \ldots, M$$

de-mixing matrices.

Clustering

- For each run, n_i ICs are estimated.
- Use a clustering algorithm (e.g., *Agglomerative Hierarchical clustering*) and dissimilarity measure (*can use the mutual correlation coefficient which is calculated via the de-mixing & the covariance matrix of the actual observations*) to partition the set of all estimated ICs into disjoint clusters

Clustering

- Use the cluster quality index to identify compact and isolated clusters.
- For each cluster and quality index, select the most central IC that is representative of the cluster.

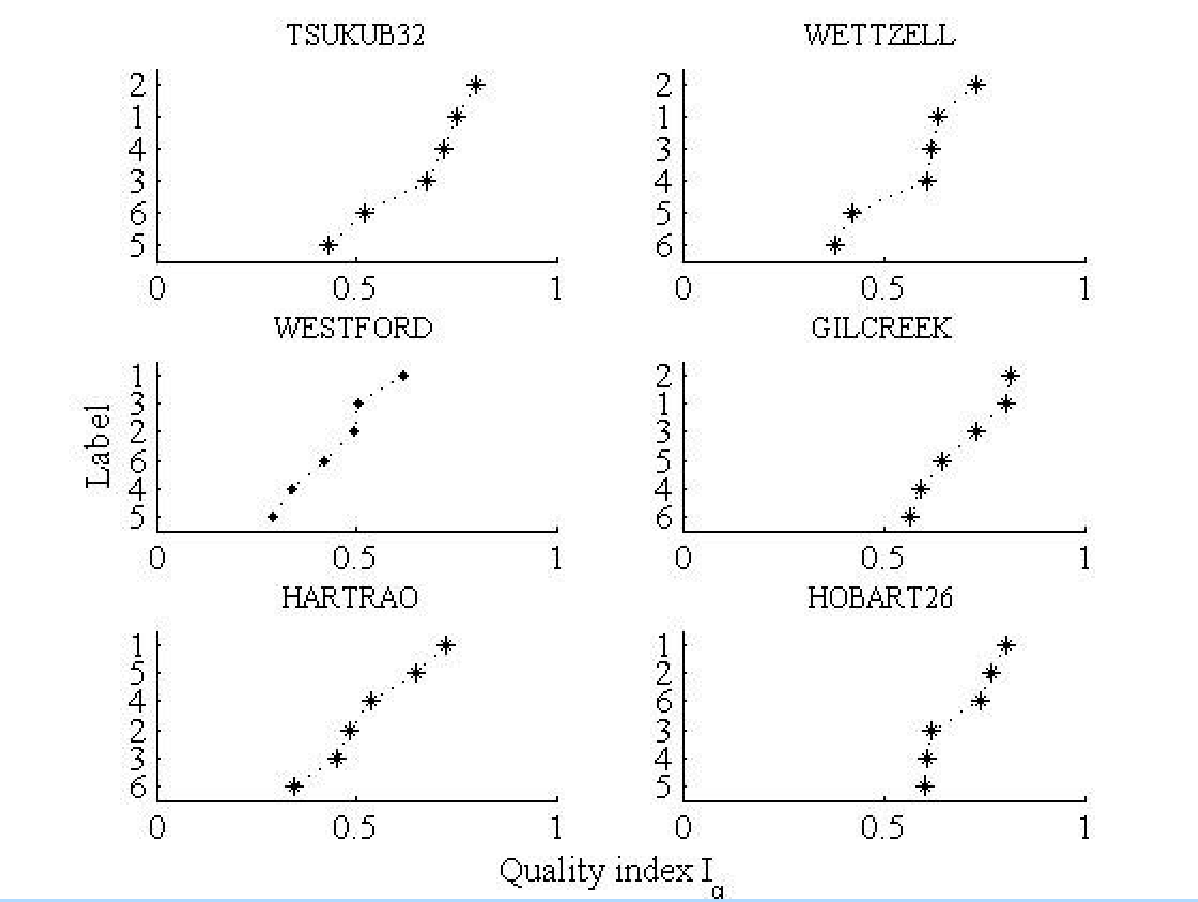

Figure 3: Ranked station dependent quality index Iq of independent components derived from zenith total delay

Method

- ❑ Phase synchronization index via the analytic signal paradigm

- Hilbert-Transform both the ICs from ZTD and the known geophysical signals

$$\xi = A_x^H(t) e^{j\phi_x^H(t)}$$

- Compute the phase difference of the analytic signal component pairs (here, *n:m* define the phase locking ratio)

$$\Delta\phi_{xy}^H(t) = n\phi_x^H(t) - m\phi_y^H(t)$$

Method

- ❑ Phase synchronization index via the analytic signal paradigm

- determine the phase synchronization index assuming a1:1 phase locking ratio

$$\eta=\sqrt{\left\langle \cos\Delta\phi_{xy}^{H}(t)\right\rangle_t^{2}-\left\langle \sin\Delta\phi_{xy}^{H}(t)\right\rangle_t^{2}}$$

Test results

❑ Adaptive decomposition of ZTD

- **# of modes (we have 7) dependent on the temporal span of the data**
- **6th & 7th modes have been combined to generate a non-linear trend.**
- **High fluctuating mode(s): 1& 2 exhibit a period ~ 1 month**
- **3rd & 4th modes have seasonal and annual periods respectively**

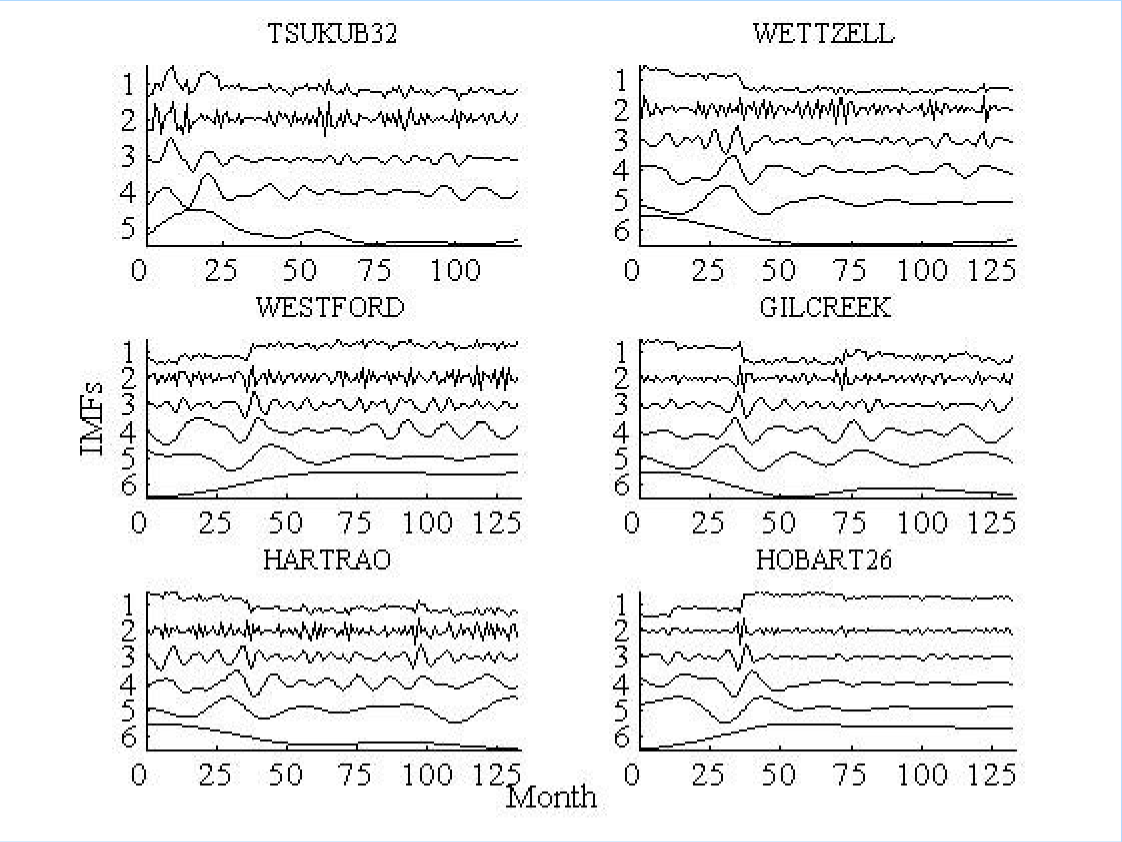

Figure 4: Empirical Mode Functions (IMFs) of ZTD series at six IVS stations with site dependent modes of fluctuations.

Test results

❑ Independent oscillatory components from ICA

- **The cluster quality index is used to rank the ICs in each IVs station**
- **Select ICs with high degree of localization.**

Station	ZTD	G.S
Tsukub32	1, 3, 4	3, 4
Wettzell	1, 2, 3, 4	-do-
Westford	1, 2, 3	-do-
Gilcreek	1, 2, 6	-do-
HartRAO	1, 2	-do-
Hobart	1, 2, 3	-do-

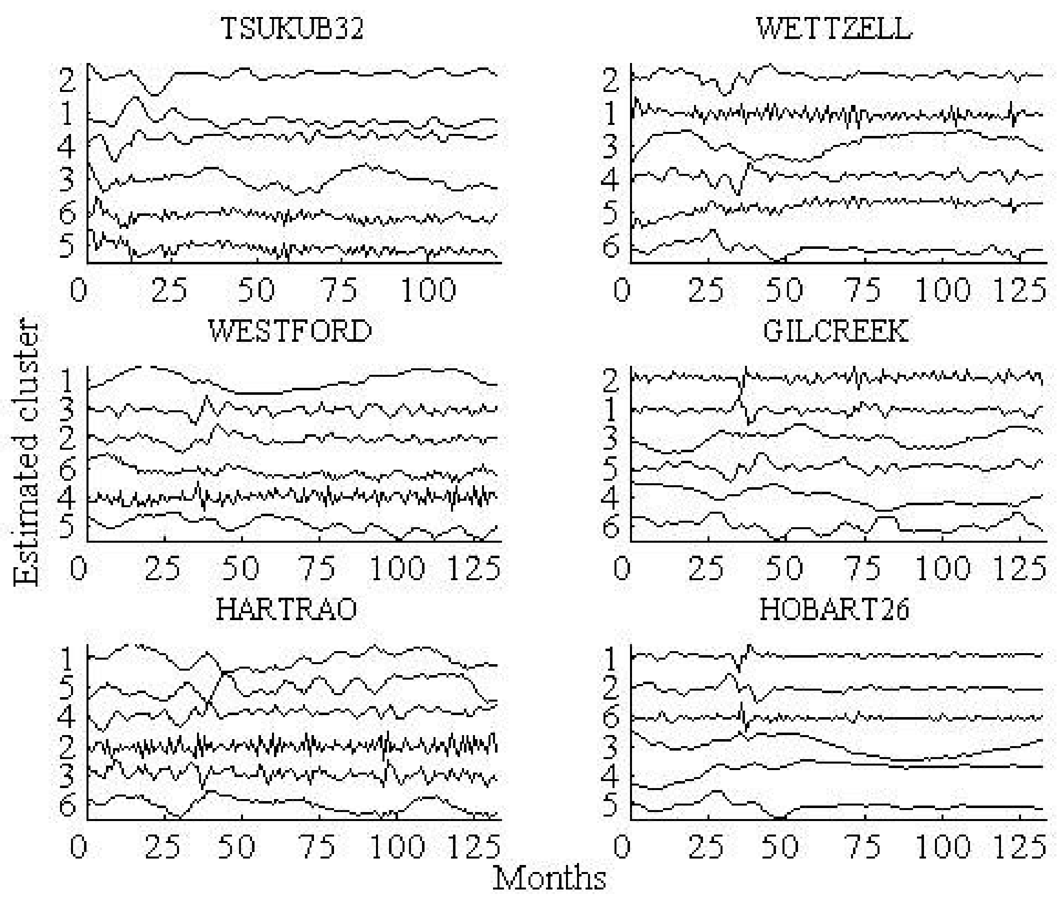

Figure 5: Estimated independent components in ZTD.

Test results

- The angle strength of the phase angle difference

Station	ZTD	η
Tsukub32	1-3; 1-4; 3-3; 3-4; 4-3; 4-4	0.47; 0.46; 0.47; 0.46; 0.47; 0.45
Wettzell	1-3; 1-4; 2-3; 2-4; 3-3; 3-4; 4-3; 4-4	0.48;0.58; 0.47; 0.62; 0.43; 0.61; 0.42; 0.53
Westford	1-4; 2-4; 3-4	0.46; 0.49; 0.46
Gilcreek	1-3; 2-3; 6-3	0.55; 0.58; 0.58
HartRAO	1-3; 2-4; 2-3; 2-4	0.54; 0.53; 0.57; 0.50
Hobart	1-3; 1-4; 2-3; 3-3; 3-4; 2-4	0.57; 0.48; 0.57; 0.49; 0.56; 0.48

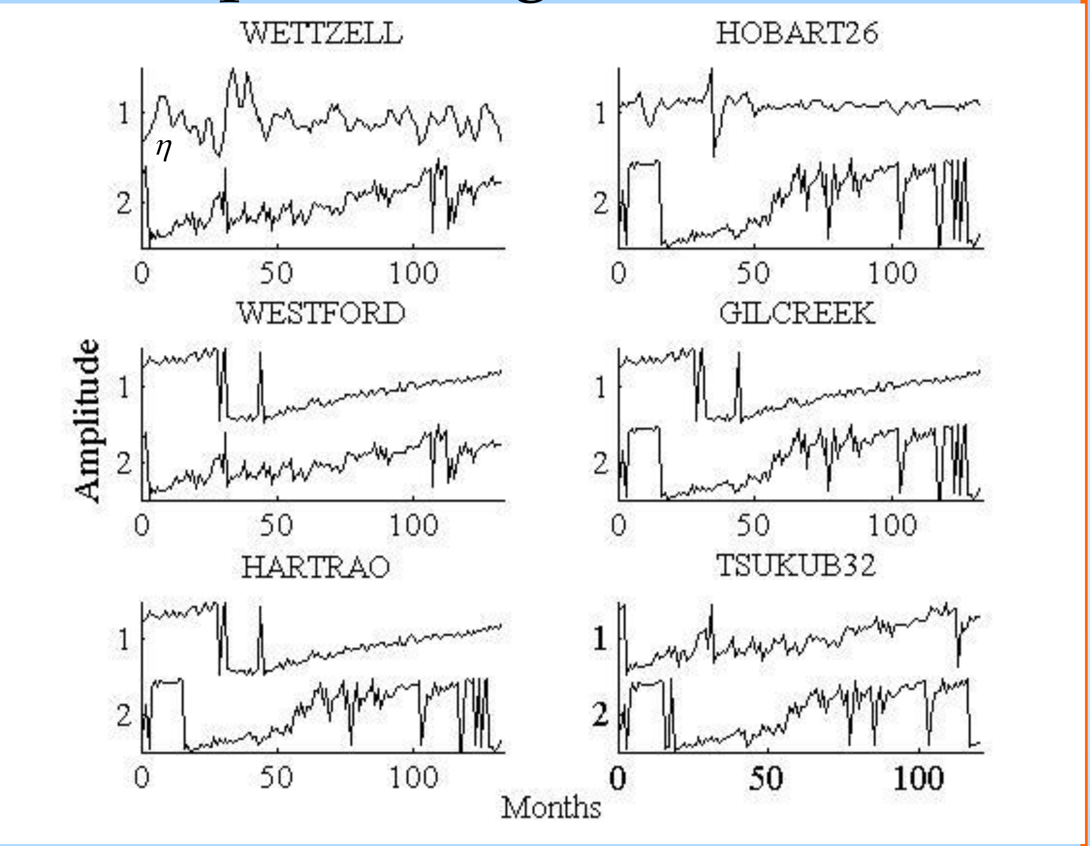

Figure 6: Phase synchrony index between pairs of geophysical signals.

Summary

☐ Non-linear dynamics

- EEMD-ICA robustly extract tractable signal components that carry important geophysical information
- The signal components exhibit spatial-temporal signature that characterises the underlying process
- ZTD signal components have dynamical coupling that exhibit spatial dependence