FLUCTUATIONS OF THE EARTH ROTATION AND EL NIÑO EVENTS

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1. MOTIVATION

We investigate the characterization of nonlinear low dimensional deterministic processes in the rapid fluctuations of Earth Rotation. We then analyze their intrinsic stability by computing the associated global and local Lyapunov exponents.. We see how the variations of that stability are related to El Niño phenomena.
The first step of our work is to apply nonlinear time series analysis techniques to daily observations $x(t)$ of the length of day (LOD) and polar motion components (PMX, PMY) spanning over more than 27 years and filtered so to keep the period range [$\approx 2day - 100days$]. Using time delay coordinates, we embed each EOP time series in a low dimensional pseudo-phase space. The dimensional and stability characteristics of the underlying dynamical process (which induces the rapid fluctuations of the Earth rotation) are then extracted from the reconstructed orbit (see below). We decide to treat those time series in a new manner because, first of all, atmospheric and oceanic flows generate the main perturbations in the Earth's Orientation Parameters (EOP) for such periods (see e.g. Eubanks 1993). The dynamics of the oceanic/atmospheric system are nonlinear and exhibit chaotic attractors on various time scales (see e.g. Nicolis and Nicolis 1984, Tziperman et al. 1994). Thus we ask the question of the transmission of these interacting complex dynamics to the short term fluctuations of the Earth Rotation. More over, the power spectrum associated to each EOP time series analysed here, is broadband: a broadband spectrum is not only revelant of a high-dimensional noise process but is also typical of a nonlinear low dimensional chaotic process (ex: the Lorenz attractor, Ruelle 1991).

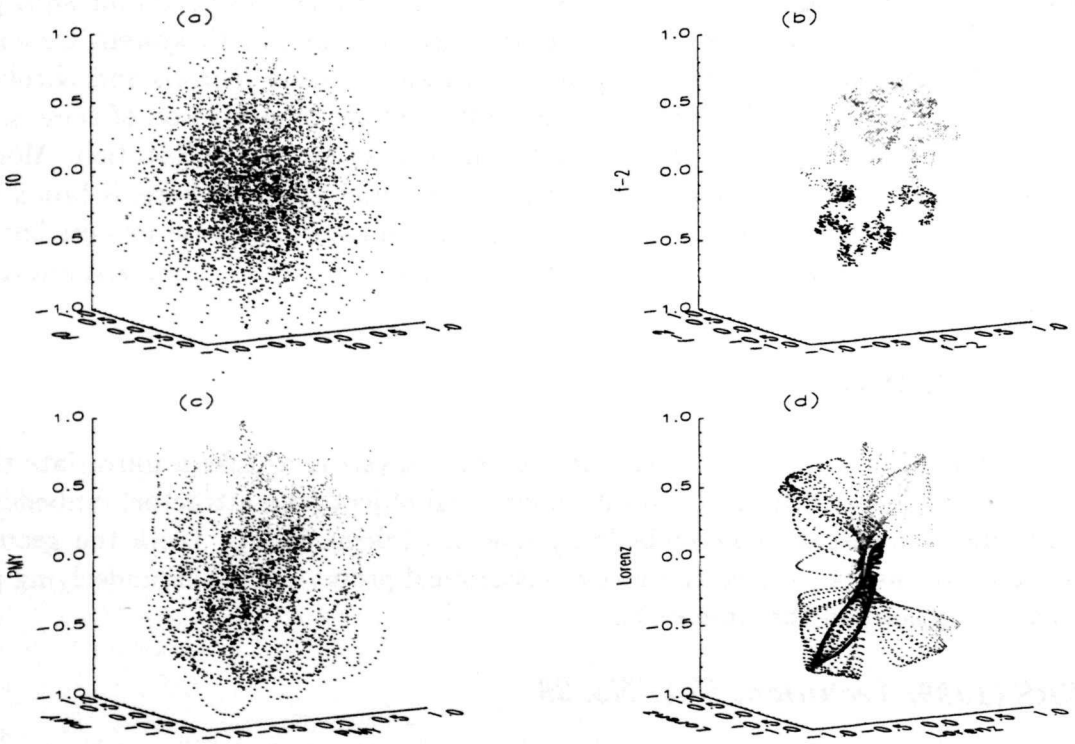
2. EMBEDDING

The main idea of the non-linear time series analysis is to take a univariate time series $x(t)$ and to build from it a multidimensional object (the attractor) embedded in a multidimensional space (the embedding space), (Takens 1981). From the geometrical properties of this object, we can recover dynamical properties of the underlying process which has generated the time series.

Embedding time delays are obtained from the Average Mutual Information function (Fraser and Swinney 1986). They are of 10 days for LOD, 15 days for PMX and 18 days for PMY.
They are used to construct the multidimensional vectors with delayed coordinates:

$$\vec{y}(t) = [x(t), x(t+\tau), ..., x(t+(D_{E^*}-1)\tau)] \quad (1)$$

The dimension of the embedding space, $D_E^* = 5-7$ is determined from both the percentage of global false neighbours and from the correlation integral methods (Grassberger and Procaccia 1983).
In order to have an idea about the phase space behaviour of the reconstructed systems, we draw 3D projections of delayed coordinates of the EOP data vectors; they are clearly different from stochastic power law noises (infinite dimensional processes) and seem to be issued from a smooth dynamical system.
Indeed the following figure shows the 3D projection of a 6-dimensional reconstruction of delayed vectors for : a) a time series of white noise, b) a time series of a random walk, d) a chaotic time series c) the time series of PMY. The results for PMX and LOD are similar. We clearly see the erratic distribution of points for the white noise, the fractal structure of the curves for the random walk and the continuous orbits for the chaotic system. For PMY, the orbits are continuous, self-crossing because the dimension required to unfold the attractor is superior to 3, (note the presence of noise in the centre of the figure). All these results can be found in details with complete discussion in Frede and Mazzega (1998a).



3. GLOBAL STABILITY ANALYSIS

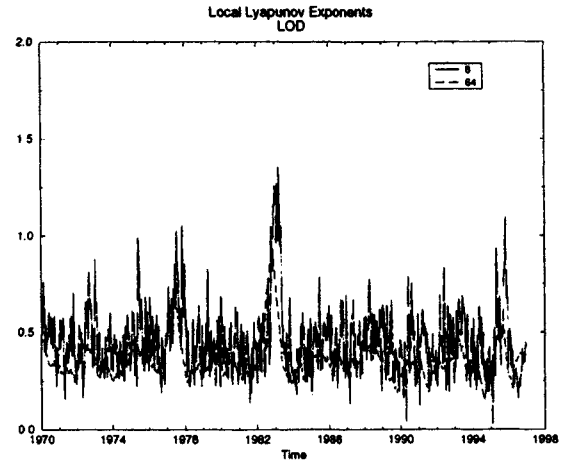
The previous part of the analysis was devoted to dimensional characterizations of the *EOP* short terms fluctuations. A stability characteristics of the underlying dynamics can also be drawn from the embedded time series. This analysis recovers the development of instabilities in the system and puts hard bounds on the time interval over which it is impossible to reliably predict the system evolution (whatever might be the method used for such prediction). First of all, the dynamical dimension indicates the exact number of active dynamical variables of the system and also gives the number of Lyapunov exponents to be determined.
Using a local false neighbours algorithm (Abarbanel and Kennel 1993) and an analysis of the data local covariance matrix eigen-spectrum, we find a local dimension $D_L = 5$ for the three *EOP* series.
The global Lyapunov exponents are indicators of the system stability. They are calculated from the eigen values of the jacobian matrix along the orbit (Abarbanel 1996). They measure the rate of contraction or expansion of an orbit perturbation taken on a local eigen-direction of the system dynamics (see below). A negative exponent implies a contraction of the orbit perturbation lying on the corresponding stable manifold. On the contrary if the system possesses at least one positive Lyapunov exponent λ_i, its time evolution is sensitive to the choice of initial conditions in a particular direction. Any small perturbation $\delta(0)$ excerted on the orbit at $t = 0$ along that direction grows exponentially with time, so that:

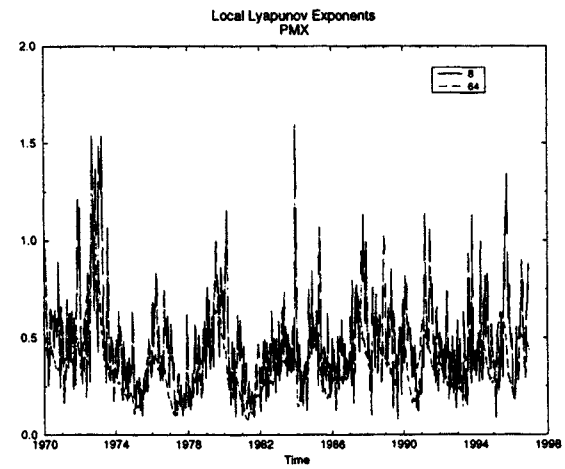
$$\delta(t) = \delta(0) exp(\lambda_i t) \tag{2}$$

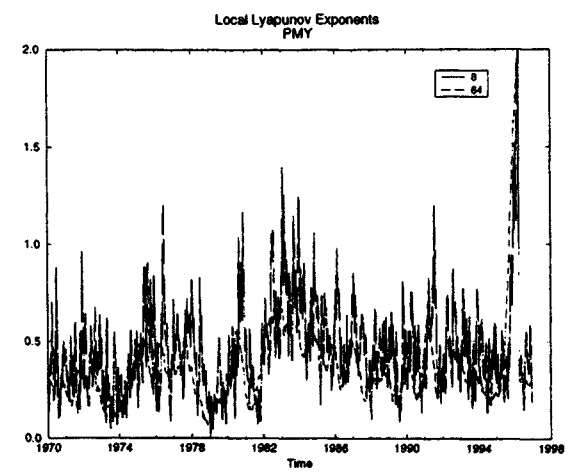
A zero Lyapunov exponent is always associated with a continuous dynamical system (a flow). Indeed it corresponds to the absence of both contraction and expansion if the perturbation is exerted along the orbit itself (neutral manifold). Systems whose sum of the Lyapunov exponents is negative are dissipative. Any volume of the n-dimensional phase space will shrink with time, though some directions may remain unchanged (along neutral manifolds) or even stretch (along unstable manifolds). The existence of positive exponents is typical of the chaotic nature of the system regime. Perturbations taken "outside" from the attractor will be damped but two orbits will rapidely separate from each other on the attractor because of the unstability.
For each *EOP* time series, we found two negative exponents, a null one with an accuracy of five per cent and two positive exponents. The principal Lyapunov exponents averaged over 1970-1997 being positive, this result unambiguously indicates the chaotic nature of the Earth's rotational dynamical regime in this period range of fluctuations. As a consequence, some theoretical prediction horizons can not be passed beyond by any tentative forecast of the the *EOP* evolution. Horizons of 11.3 days for *LOD*, 8.7 days for *PMX* and 8.1 days for *PMY* are found beyond which prediction errors will be of the order of the *RMS* of the filtered *EOP* series.

4. LOCAL STABILITY ANALYSIS

The previous evaluations are global ones, but locally, there can exist variations of the stability induced by the own dynamics of the system or by external solicitations. The stability variations of the reconstructed orbits are analyzed by the determination of their local Lyapunov exponents. These exponents are computed from the eigenvalues of local jacobian matrices retrieved from the embedded EOP time series.
The following figure shows the Local Lyapunov exponents for a) LOD, b) PMX and c) PMY respectively. It is more exactly the temporal variations of the principal Lyapunov exponent.







We have chosen two windows for its evaluation: the first one of 8 days gives us the rapid fluctuations of stability while the 64 days gives us a sort of smoothing of the stability over 2 months. This is done to obtain a compromise between the noise level and short expected variations. We remark the same event appears earlier for the second window. This is due to the fact that on the one hand the algorithm evalutes 8 jacobian matrices while 64 on the other hand. So the same phenomena at a time t will be seen earlier in the second case (because of the larger window of the moving average).
We see that the Earth's rotational state experiences large changes in stability with regard to the average chaotic regime. Moreover the local prediction horizons, as deduced from the local Lyapunov exponents, occasionally drop down to about 3.3 days for LOD in the years 1982 - 1984, 2.6 days for PMX in 1972-1973 and 2.6 days for PMY in 1996-1997. The main momentary stability perturbations of the Earth rotation are clearly related to El Niño and La Niña events (e.g. 1982-1984, 1972-1973). The 1996 loss in stability for the PMY lacks an obvious source mechanism.
This means that the observed loss of predictability of the Earth Orientation Parameters is directely related to the stability loss of the ocean/atmospheric system.
We must keep in mind that it is not surprising that a same El Niño does not have the same effect on the 3 EOP time series stability, the stability of a system depending on the system state. More over another source of excitation may hapen at the same time masking partially an El Niño forcing. We musn't confuse the time series itself with the time series of the stability variations. Here we are not looking at the correlation between El Niño events and the EOP time series but at the repercution in term of predictability of geophysical forcings on the short term fluctuations (less than 100 days) of the EOP.
The following table gives dates of events and associated horizons of prediction (in days) for the EOP time series (see Frede and Mazzega (1998b) for more details).

Series	**LOD**	**PMX**	**PMY**
Date of events			
1972-73	7.8	3.3	10.2
1976-77	11.8	7.8	7.8
1977-78	5.6	19.5	6.5
1979-80	11.8	5.2	10.2
1982-84	2.7	9.8	4.9
1987-88	11.8	6.5	7.8
1991-92	11.8	5.6	4.9
1995-97	6.5	4.3	1.9
Global mean values	11.8	11.5	10.2

5. CONCLUSION

Dimensional and dynamical characteristics of the nonlinear processes inducing the rapid fluctuations of the Earth rotation have been extracted from the *LOD* and Polar Motion filtered time series. It is in particular shown that some instabilities develop in the Earth rotation under a chaotic regime. Moreover these instabilities are magnified in those period of ENSO activity of the ocean-atmosphere system. As a consequence, the horizon of predictibility of the *EOP* time series in this frequency band, is limited to 10-12 days in the average but to only 2-3 days when El Niño and La Niña events perturb the Earth rotation. It will be interesting to perform the same analysis when longer and more precise *EOP* time series are available and look then at the repercution of the 1997-1998 recent El Niño on the *EOP* stability.

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