THE HYDROLOGIC INDUCED STRAIN-TILT SIGNAL – A REVIEW

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Abstract

A discussion of the ambient factors influencing deformation measurements undertaken with strain-tilt gauges is made. The factors which are mostly disturbing are determined, which turn out to be the hydrologic agents. The induced signals are first qualitatively described, relying on published observations and those of the NE-Italy strain-tiltmeter network. A quantification of the maximum expected signals is made. Different types of statistical and physical models which attempt to model the induced signals are discussed and tested. Among them a new approach, which relies on the techniques of predictive filtering is introduced. The methods applied for the modeling of the strain/tilt induced signals are valid also for the study of the induced signals in gravimeters.

Introduction

The deformation measurements being made at or not far from the earth's surface, they always suffer from disturbing ambient factors as temperature, hydrologic agents and air pressure. Among these agents the temperature is the most predictable, as it is closely tied to the position of the earth with respect to the sun. A well-defined yearly cycle and a periodicity of the solar day are thus an obvious consequence on the measurements. Much more complex is the time variation of the latter two agents. The hydrologic agents comprise the rainfall and its surface or subsurface runoff and the watertable variations. The two quantities are not independent. The hydrologic agents are largely aperiodic, and influence deformation measurements on a broad band of frequencies ranging from short-term variations (days) to long term variations (several years). Apart from coseismic deformation steps, the deformation which should accompany the preparation of a seismic event, according to theoretical considerations (Lorenzetti and Tullis, 1989; Scholz et al., 1973; Scholz, 1990: ff 362), covers the entire range from long period (several years) to short period deformation (days) shortly before the event. The similarity in the time constants involved makes the hydrologic induced signals particularly disturbing in deformation studies aiming at detecting tectonic movements.

The influence of air pressure compared to the hydrologic induced signals has been studied for time variations slower than two days. Nine months of borehole tilt in the English Lake District (Edge et al., 1981) were studied together with air pressure and water table level measurements. The tilt was recorded at 12-m depth with two Askania tiltmeters. The regression coefficients gave 2 msec/hPa (0.01 microrad/hPa) for pressure and 200 msec/m (1 microrad/m) for watertable variations. These values translate to maximum induced signals of approximately 20 msec (0.1 microrad) and 200 msec (1 microrad), for pressure and watertable respectively.

A study of the strain measurements of three horizontal strainmeters installed at 60-m depth in a cave in NE-Italy gave a similar ratio of the barometric and hydrologic induced effects. In this case the hydrologic agent was measured in the quantity of rainfall, and the regression analysis found 4-5 nstrain/mm rainfall, which amounted to a maximum value of several 100 nstrain (Dal Moro and Zadro, 1998). The effect of pressure on strain gave a coefficient of 2 nstrain/hPa, which amounts to a maximum value of about 20 nstrain. These values are not very different from those found for the Cambridge-type extensometer array at the Black Forest Observatory (BFO) in SW Germany at higher frequencies. According to Dr. Walter Zürn (personal communication) at periods between 1000s and 3000s coefficients between 0.5-0.8 nstrain/hPa were found. As also for the tilt in the English Lake district, the hydrologic induced signal in NE-Italy is at least 10 fold greater than the air pressure induced effect at frequencies lower than 0.5 cpd.

In the present paper we intend to study only the hydrologic induced deformation, giving a characterization of and presenting the different models which attempt to reproduce the signals. There are some uncertainties regarding the physical nature of the induced deformation. Evans and Wyatt (1986) attribute the deformation to changes in the aperture of subsurface hydraulically conductive fractures due to pore pressure changes and to compaction due to porosity changes induced by changing pore pressure. A different model considers the deformation of the rock matrix due to pore pressure gradients leading to groundwater flow in the pore space (Kümpel, 1986; Kümpel, 1989).

Characterization of the hydrologic induced deformation

The hydrologic induced deformation is characterized by a typical time evolution, which is found both in extensometer and in tiltmeter records. The onset is rapid, almost steplike with a near to exponential recovery. The azimuth of the tilt signal is typical for each station. Edge et al. (1981) find the induced tilt to be oriented perpendicular to the strike of the cleavage planes of the slate forming the bedrock. Peters and Beaumont (1981) find a strong dependence of the tilt signal on the orientation of the structures at depth permeated with water.

The extensometric signal may be either compressive or dilatational, which can depend at a certain station on the azimuth. The sign of the deformation is though generally constant (Wolfe et al., 1981; Yamauchi, 1987). Tanaka et al. (1989) find compression for two strainmeters and extension or compression for a third extensometer in accordance to a rain threshold.

Long term fluctuations in annual precipitation may lead to slow variations in the watertable level, which have been made responsible of long term influences on the deformation measurements (Kasahara et al., 1983).

Modeling of the induced signals

An important task is the modeling of the induced signals, with the scope of cleaning the observations from the hydrologic influence. Two different approaches can be made, which is to create statistical models that describe the signals or to reproduce the physical nature of the problem as close as possible. In the following we present various statistical methods together with some examples.

The most straight forward way to detect the influence of rainfall is to compare rainfall with some component of deformation, as the tilt or extensometric record, or composite quantities as the areal deformation, total tilt, etc. This method, although widely used, is not convenient as it does not compare the correct quantities. The induced signal depends on the entire history of rainfall, whereas the rainfall histogram considers the rainfall over definite limited time intervals (for example day or half a day). The rainfall series is different also from a statistical point of view, as it has only positive or zero values, which is not the case for the time series of a deformation component. The consequence is that the correlation coefficient between rainfall and a deformation record appears to be low, although by visual inspection it is evident that the onset of rainfall is responsible for a deformation signal.

With a simple mathematical procedure it is possible to obtain two time series which can be compared. The first is to integrate the rainfall over the entire time interval and subtract an average linear trend. Be $p(n)$ the sampled rainfall, $\overline{\dot{p}}$ the average time derivative of rainfall, then the rainfall function I $r(n)$ is defined by:

$$r(n) = \sum_{k=0}^{n} p(k) - \bar{p}\, n\, \Delta t \qquad (1),$$

with Δt the sampling interval.

Another procedure is to evaluate the time derivative of the observed deformation (or a composite quantity as areal strain, total tilt, etc.) and compare it with rainfall. In Fig. 1

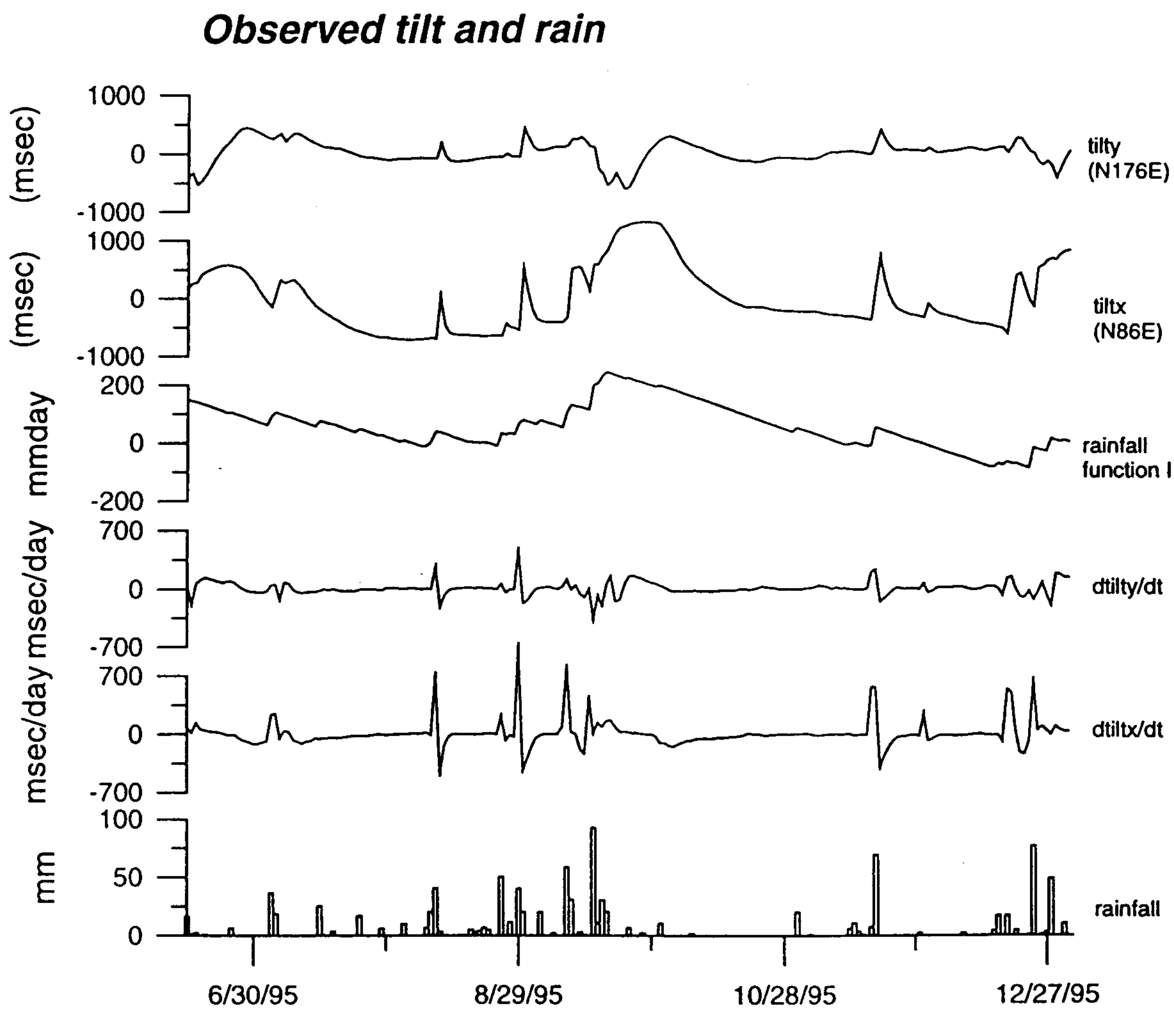

Fig. 1 – Different ways to evaluate the influence of rainfall on tilt observations by visual inspection. For the second half of the year 1995 the rainfall, the time integral of rainfall minus a linear trend (rainfall function I), the time derivative of tilt and the tilt observations are shown. The tilt observations refer to a reference system aligned with the orientation of the induced tilt (N86E).

rainfall, the rainfall function I (Eq. 1), the time derivative of the two tilt components and the two tilt components are graphed for the second half of year 1995. The rainfall and tilt measurements refer to the Friuli (NE-Italy) strain-tiltmeter network installed in 1977 (Zadro, 1978). Rainfall is furnished by the Italian Government service (Magistrato delle Acque, station Vedronza) with daily sampling. The relative distance between the tilt and rainfall station is 9 km.

The tilt observations are made in a natural cave at the Gemona station with Zöllner type horizontal pendulums. Details about the station and the network are described in Braitenberg (1998). The tilt data have been reduced from hourly to daily sampling, after having applied an antialiasing filter. The long term drift and yearly thermoelastic deformation have been taken off by least squares adjustment with the sum of a fourth order polynomial and a sine and cosine function of 1 year period. Remaining long period signals have been taken off by high pass filtering with cut off period of 30 days. The reference system of tilt has been rotated so as to align one axis with the orientation of maximum hydrologic induced deformation. This orientation was obtained from the principal direction of the ellipse describing the angular distribution of the mean square tilt amplitude (tilt cleaned from long period time variations). For the year 1995 the mean orientation of the greatest and least square tilt amplitude is oriented N86E and N176E, respectively. The correlation coefficients of rain or the rainfall function I (Eq. 1) with the tilt observations and the tilt time derivatives are given in Table I. The values refer to the second half of year 1995.

The Table I shows that the correlation coefficients of rainfall with the tilt components would erroneously demonstrate that the tilt measurements were independent from rainfall. Use of the rainfall function I or the time derivative of the tilt measurements for the correlation analysis reveals that hydrologic influence does exist.

Langbein et al. (1990) considered the influence of rainfall on repeated length measurements of geodetic baselines near Parkfield, California. They introduce a rainfall function II that has great similarities with the above rainfall function I. It is a cumulative function of rainfall, but rainfall is convolved with an exponential function with a time constant *(τ)*. The rainfall function II is defined as:

$$r(n) = \sum_{k=1}^{n} p(k) e^{-\left({(n-k)\Delta t}/{\tau} \right)} - \bar{p}\, n \Delta t \qquad n \geq k \qquad (2)$$

As in eq(1) a linear trend given by the average time derivative $\bar{p}$ is subtracted. The method has been applied successively by Bella et al. (1995) for correcting observed tilt variations.

	Tilt x	Tilt y	Time derivative Tilt x	Time derivative Tilt y
rain	0.002	-0.000	0.525	-0.018
Rain function I	0.703	-0.147		

Tab. I – The correlation coefficients of rain or the rainfall function I and the tilt observations or their time derivatives are reported. The time interval is the second half of year 1995. The time series refer to those graphed in Fig. 1. The tilt components refer to the reference system rotated by 86° clockwise, which is the direction of greatest amplitude for the induced deformation.

Wolfe et al. (1981) find strong influence of hydrologic agents in strain data from a Benioff type gauge installed in the Kipapa tunnel (Oahu, Hawaii). The tunnel is located at 30m depth beneath weathered basalt. An empirical model for the rain-strain relationship is developed that uses two known hydrologic mechanisms, infiltration and recession (outflow of water from the ground). They find the following expression for the rain-induced strain ($e(t)$):

$$e(t) = \alpha f t \qquad 0 \le t \le t_c$$
$$e(t) = \alpha f t e^{-(t-t_c)/\tau} \qquad t_c \le t \le \infty \tag{3}$$

with

α = transfer value from rainfall to strain

f = infiltration rate

t_c = duration of rainfall

τ = time constant

The time constant (τ) takes inflow of water through the porous aquifer and exponential recession into account. The application of the model to observed data gives transfer values (α) in the order of 10 nstrain/mm. The time constant of the exponential decay ranges from 20 to 50 hours.

Yamauchi (1987) studies the effect of rainfall on 10 years of crustal strain (extensometer and tiltmeter) at Mikawa crustal movement observatory, Central Japan. The induced strain is modelled by a simulated outlet of a series of 3 concatenated tanks, which has a nonlinear response to the incoming rainfall. The tank model has been used also in the simulation of groundwater flow. Each tank obeys the differential equation:

$$\dot{H}(t) = P(t) - \alpha H(t) - a_1(H(t) - H_1) - a_2(H(t) - H2) \tag{4}$$

with

$$a_i = \begin{cases} \text{constant } (\neq 0) & H(t) \ge H_i \\ 0 & H(t) < H_i \end{cases}$$

where $H(t)$ is the waterlevel in the tank at time t, $\dot{H}(t)$ is the time derivative of $H(t)$, and H_1, H_2 are two levels at which the outlets are set. The input flow to the successive tank is given by:

$$O(t) = \begin{cases} a_1(H(t) - H_1) & H(t) \ge H_1 \\ 0 & H(t) < H_1 \end{cases}$$

The second tank behaves in analogous way, its outlet being fed into a third tank. The waterlevel of the third tank simulates the strain response to rain. The equations must be numerically solved and the parameters adapted by trial and error. The examples shown are promising and partly reproduce the induced signals well; the authors claim that they were able to correct 90% of the effects of rainfall over a 10 years observation period. One problem in the general application of the method is that the determination of the parameters is made with trial and error, which is a time consuming approach.

An innovative method is given by the techniques of predictive filtering. The subclass of the autoregressive (AR) time series model is defined by

$$x(n) = -\sum_{1}^{m} a(k)x(n-k) + u(n) \tag{5}$$

in which *x(n)* is the output sequence of a causal filter modeling the observed data and *u(n)* is an input driving sequence (Marple, 1987; p.174). The parameter *m* defines the order of the AR-model. The *a(k)* parameters define the filter, and can be obtained as solutions to linear equations. Marple (1987) gives an ample discussion on the different algorithms with which the *a(k)* parameters can be calculated, given the model order *m* and the sequence to be modeled *x(n)*.

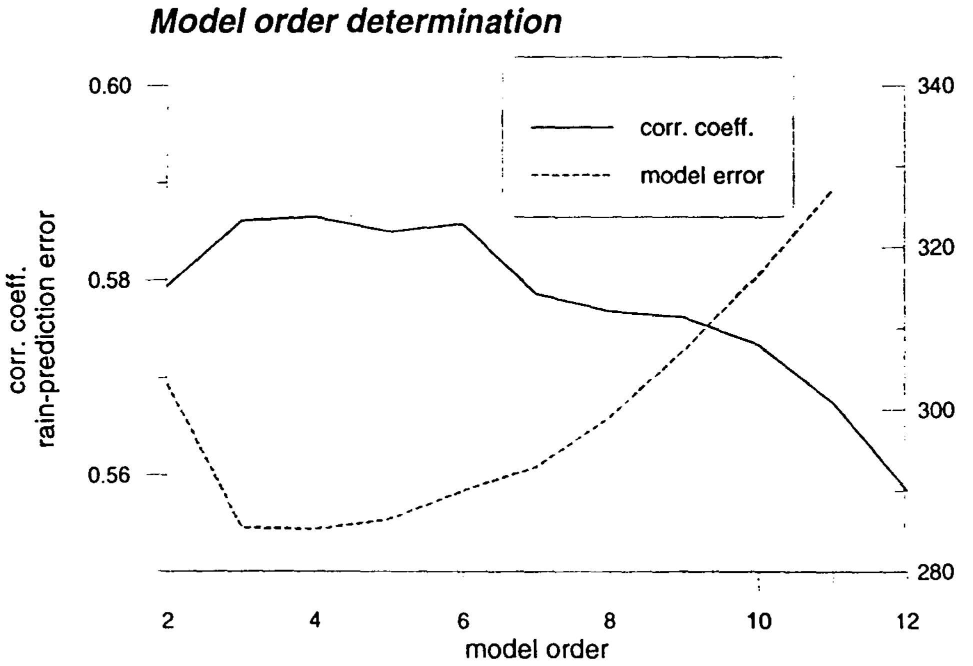

Fig. 2 – Two statistical quantities for determining the model orders: 1) correlation coefficient of rainfall and the theoretical driving sequence (fpe) obtained for different orders of the AR model, 2)model error, equal to the root mean square of the difference of the observed and predicted rain induced tilt for different model orders. The quantities are extreme for model order equal to 4.

The choice of the model order *m* constitutes a problem, for which we propose two solutions. Both solutions base on the postulate that the AR-model obtained should represent the portion of observed data which is rain induced. Consequently the driving sequence *u(n)*, should be equal to the rainfall multiplied by an appropriate scaling factor (units msec/mm),

$S\,p(n)$. Given the AR model, we may calculate for the first solution a theoretical driving sequence, which is equal to the forward prediction error (fpe):

$$e_m(n) = \sum_{k=1}^{m} a(k)x(n-k) + x(n) \qquad (6).$$

We apply the criteria of maximizing the correlation coefficient of rainfall and the theoretical driving sequence ($e_m(n)$) for different model orders m.

The second criterion bases on the postulate that the modeled data sequence should be as close as possible to the observed data, given the rainfall as the driving sequence. With $\overline{p}$ the time average over the studied period of rainfall, we define the error of the induced signal by

$$\Delta_m(n) = x(n) - \left[S_m\left(p(n) - \overline{p}\right) - \sum_{k=1}^{m} a_m(k)x(n-k) \right] \qquad (7),$$

in which S_m is a scaling factor. The scaling factor (S_m) is equal to the ratio of the mean square root amplitude of the fpe ($e_m(n)$) and the rainfall ($p(n)$). We choose that particular model order m for which the root mean square amplitude of the model error ($\Delta_m(n)$) is minimized.

As an example we apply the predictive filtering method to the data series shown in Fig. 1. The estimation of the AR-model parameters can be made on a block of data, obtaining an average model, or in an adaptive way, by which slowly varying model parameters are obtained. For the present case we have applied the gradient least mean square (LSM) adaptive algorithm, which is a robust adaptive method (see e.g. Marple, 1987), in which the parameters are recursively corrected at each data point, according to

$$a_k(n) = a_k(n) - u\nabla\left(e_m^2(n)\right) \qquad k = 1, m \qquad (8)$$

with $e_m(n)$ the fpe at the step n, and u a convergence factor. The convergence factor u adjusts the amount of correction made at each step. In order to guarantee stability of the algorithm, it should be chosen as $u < \dfrac{1}{m\,w}$, with w the mean square amplitude of the fpe and m the model order (Marple, 1987).

The gradient LMS method has been applied to 6 months of tilt recordings of the Gemona station (see Fig.1). As explained above, the data have been reduced to daily sampling rate and freed from long period signals. The component aligned with the preferential orientation of the induced signal was modeled (tiltx). The most appropriate model order has been obtained from the two criteria of maximum correlation coefficient of the fpe and rainfall and the minimum root mean square amplitude of the error on the predicted rain induced tilt. The two quantities are graphed in Fig. 2 for different model orders, and are seen to obtain extreme values (maximum and minimum, respectively) for a model order equal to 4. The scaling factor S_4 resulted to be 13 msec/mm (63 nrad/mm) rainfall. The convergence factor was chosen u = 5 10^{-8} for all orders examined in Fig.2. The modeled rain induced tilt (light trace), the observed tilt (heavy trace) and the fpe are graphed in Fig. 3. Comparison with Fig. 1 reveals the great similarity between the fpe and the time derivative of the tilt signal (dtiltx/dt). The agreement between the fpe and rainfall is partial, which may have different reasons. First, the observed tilt signal is a combination of tectonic and ambient factors, and each of these parameters constitutes a driving sequence to the signal. Second, in the particular case of the Gemona station, the pluviometer is located 9 km away from the observation station, which in mountainous areas can lead to significant differences in the observed rainfall. Nonetheless, in Fig. 3. one can see that the algorithm is apt to identifying the portions of the observed tilt which are rain induced.

The time variation of the four autoregressive parameters is shown in Fig. 4. The parameter of first order is almost five times greater in amplitude than the parameter of second order and

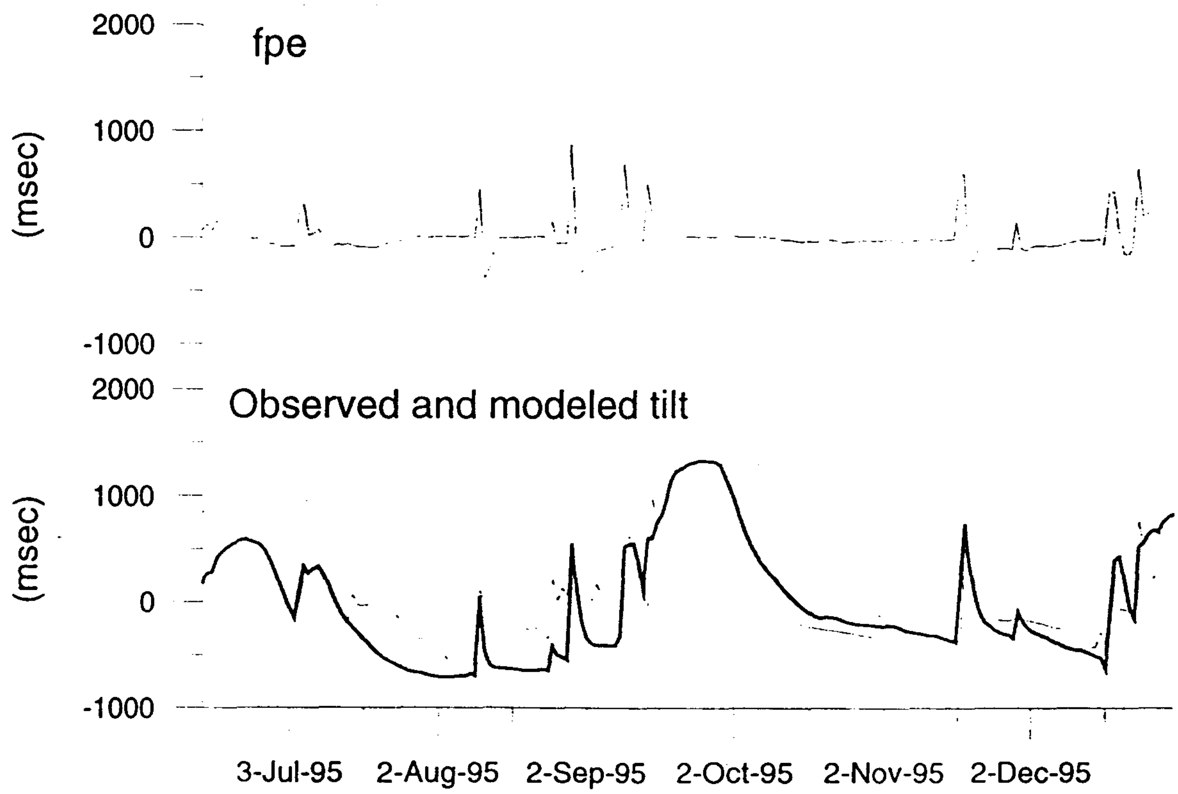

Fig. 3 – Modeled (light trace) and observed (heavy trace) hydrologic induced deformation of tilt at GE - station. Original records freed from long period signal and reduced to daily sampling. Also shown is the forward prediction error (fpe)

nearly an order of magnitude greater than the parameters of third and fourth order. This explains the great similarity between the fpe and the time derivative of tilt.

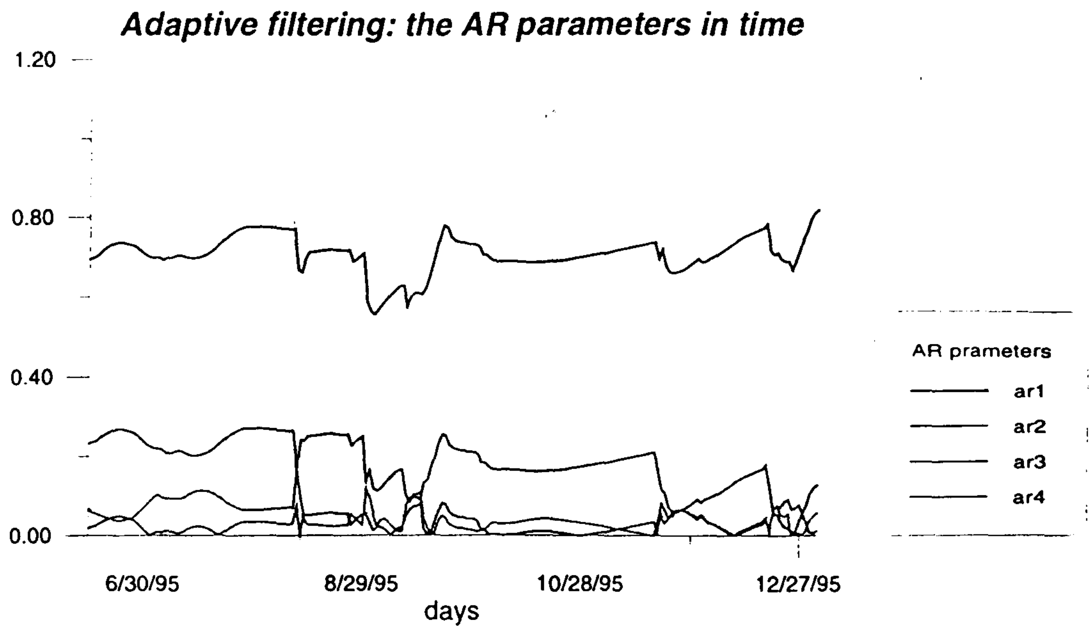

Fig. 4 – The time variation of the AR-model of the tilt recorded at Gemona station.

Conclusions

A number of techniques have been exposed which aim at solving the problem of identifying and modeling the hydrologic induced effects in deformation measurements. It has been shown that erroneous results regarding the correlation coefficient of the hydrologic agent and the observed deformation are achieved, if the two time series are not appropriately analyzed. The rainfall is to be compared to the time derivative of deformation, the deformation to a time integral function of rainfall. Among the statistical models, the linear prediction filters have given good results for the modeling of the hydrologic induced signals. In the example shown though, the reliability of the modeled induced signal is not such, that it can blindly be used to subtract the induced signals from the records. In the case of the Friuli measurements two main reasons can be made responsible for this: first, the daily sampling rate of rainfall is too low and should be increased. Second, the pluviometer is located at several km away from the observation station, which in mountainous areas could cause some differences between the observed rainfall and the one influencing the tiltmeter.

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