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Time Series Modeling of the Hydrologic Signal in Geodetic Measurements

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Abstract

The techniques of autoregressive time series modeling by recursive filters are used to study and model the hydrologic induced signal in geodetic measurements. In particular, the recordings of tilt and extensometers installed in the seismically active Friuli area of NE-Italy are used in this study. The hydrologic influence is described from a statistical point of view, rather than from the physical processes that are involved. The time stability of the induction process is also studied. The method allows to discriminate hydrologic induced deformation signals from those due to pre/postseismic tectonic deformation.

1. Introduction

It is out of question that geodetic measurements, also if made underground at several tens of meters below the surface, measure deformation due to non-tectonic effects, as rainfall, temperature variations and atmospheric pressure. The induced signals are superimposed to the signal to be measured, which can be earth tides, free oscillations or crustal deformation due to tectonic movements or volcanic activity (Zadro and Braitenberg, 1999). In crustal deformation experiments, it is often not clear what the nature of the tectonic signal should really be, especially regarding the medium term and long term variation. Adequate understanding of the signals induced by atmospheric agents are then a means to test the reliability of the measurements, as the acting agents, like temperature variations, rainfall and pressure variations are rather well known. A quantitative analysis of these effects is thus mandatory for all deformation stations (Garavaglia et al., 2000). As the magnitudes of the induced signals may be comparable with or even greater than the tectonic signals in underground measurements, it is expected that also surface measurements, as continuous GPS, suffer from these agents.

From a physical point of view, the most straightforward influence appears to be the thermal effect: the induced deformation is proportional to the temperature variation, and is related to the thermal expansion coefficient. The temperature variation at depth is governed by the relevant thermal conductivity of the geologic formations, whereby a damping of the effect and a phase shift of the temperature variation at depth with respect to the surface temperature is to be expected (e.g. Lowrie, 1997, p.189). Estimation of the atmospheric pressure effect requires an adequate model of the atmospheric pressure, which is applied as a load to a halfspace. Studies involving FE-modeling have shown that the induced effect depends on the topography, the shape

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of the underground cavity, and the position of the instruments (e.g. Dal Moro et al., 2001).

Still more complicated is the hydrologic induced effect, as it depends not only on the surface and subsurface run-off of the precipitation, but also on the level of the water table. Direct modeling (Kümpel, 1989) is thus rather difficult. In a previous paper (Braitenberg, 1999a) it was shown that statistical modeling of the hydrologic effect is possible by applying the techniques of digital recursive adaptive filters. Whereas in the previous work emphasis was put on the methodology used for estimating the filter coefficients, it is here intended to test the performance of the modeling on extended data series. Furthermore, the deformation records obtained during the occurrence of two significant seismic events shall be investigated, as the recognition of a tectonic signal from a hydrologic induced signal is crucial for the separation of a possible pre-, co-, or postseismic deformation.

2. Statistical Model

The linear filters we intend to apply are of the autoregressive (AR) type expressed by

$$x(n) = -\sum_{k=1}^{p} a(k)x(n-k) + u(n)\,. \tag{1}$$

Herein $x(n)$ is the output sequence of a causal filter that models the observed data and $u(n)$ is an input driving sequence (Marple, 1987; p.174). The $a(k)$ parameters form the AR coefficients of the model. The parameter p indicates the AR order of the model. In adaptive linear filter theory, the parameters $a(k)$ of the filter are allowed to vary in time. The unknowns of the modeling procedure are the model order p and the model coefficients $a(k)$. The techniques developed in the theory of AR modeling provide solutions for solving the coefficients $a(k)$, once the model order of the filter is defined. Given the recorded deformation $x(n)$ and the rainfall $r(n)$ we may apply two methods to determine the model order p that best represents the hydrologic influence. The first involves the definition of the forward prediction error (fpe):

$$e_p(n) = \sum_{k=1}^{p} a(k)x(n-k) + x(n)\,. \tag{2}$$

In the case of a hydrologic induced deformation the rainfall $r(n)$ takes the role of the driving sequence. The correlation coefficient between the fpe and rainfall is thus evaluated for different model orders, choosing that order p which maximizes the correlation coefficient.

As an alternative solution the rainfall is assumed to be the driving sequence and fed as input to the AR model. The model error is evaluated by

$$\Delta_p(n) = x(n) - \left[S_p(r(n) - \bar{r}) - \sum_{k=1}^{p} a_p(k)x(n-k) \right], \tag{3}$$

in which S_p is a scaling factor and $\bar{r}$ is the mean rainfall over the analyzed period. The scaling factor (S_p) is equal to the ratio of the mean square root amplitude of the fpe ($e_p(n)$) and the mean standard deviation of rainfall ($r(n)$). That order p is chosen for which the mean square root amplitude of the model error ($\Delta_p(n)$) is minimized.

3. Application to Extensometric Recordings

The methodology is applied to signals of extensometric measurements made in NE-Italy, where a network of five deformational stations has been deployed since 1977 in a seismically active area (Braitenberg, 1999b). All of the stations are equipped with tiltmeters of the Zöllner type built at the University of Trieste (Marussi-tiltmeters). One station also has three horizontal Invar wire strainmeters of the Cambridge type. The data are recorded with hourly sampling rate. Rainfall is recorded at a daily sampling rate in the vicinity of the stations by regional governmental institutions (Magistrato delle Acque). In order to have the same sampling rates, the deformational recordings must be reduced from hourly to daily sampling,

The rainfall induced deformation is characterized by a rapid onset and a near to exponential recovery, with a time constant of several days. It is therefore justified to free the deformational records from secular trends and from the seasonal cycle by numerical high pass filtering. An eight year long sequence (1990-1998) of one of the horizontal strainmeters (ST4, azimuth (α)=N67E) is high pass filtered at five cut-off frequencies (f1=1/400 cpd, f2=1/200 cpd, f3= 1/100 cpd, f4= 1/50 cpd, f5=1/30 cpd). The filter is applied in frequency domain, it is one from the Nyquist frequency to the cut-off frequency, and goes to zero at lower frequencies with a cosine taper. In order to find an optimal cut off frequency for the filtering, the correlation coefficient of the fpe and the rainfall is evaluated for different cut off frequencies for each year. If the correlation coefficient remains low for any model order p it is due to the fact that the signal contains contributions that mask the hydrologic induced effect.

In table 1 the maximum and minimum correlation coefficients are given for each year, together with the cut-off period which gives the largest correlation coefficient. The last column gives the numerals of the months for which the analysis was carried out. The selected interval is conditioned by the data-availability and the presence of rainfall. Although some variation with time is evident, a cut-off period between 100 and 200 d was found to be the most adequate. The correlation coefficients are mostly well above 0.5 with a maximum value of 0.73. The intervals with low correlation coefficients are generally characterized by reduced rainfall.

Table 1. Correlation coefficients of rainfall and forward prediction error calculated for successive years. Also shown is the cut-off period of the high pass frequency filter that, applied to the data, gives the maximum correlation coefficient. Column "Months" indicates months in the year used for the calculations.

	Max/min corr. Coeff.	Cut-off period (d)	Months
1990	.54/.49	200	3-12
1991	.60/.47	200	1-6
1992	.54/.45	200	1-12
1993	.50/.38	100	3-12
1994	.44/.33	200	1-12
1995	.57/.46	100	1-12
1996	.73/.58	100	1-5
1997	.63/.45	100	5-12
1998	.57/.28	200	1-12

The analysis confirms that the rain induced signal hardly affects the secular and seasonal terms of the records, and is more important for variations with periods shorter than 4-5 months. The hydrologic signal in the extensometric records is now studied at the occurrence times of two seismic events, that had favorable magnitude/distance relations with respect to the Villanova station.

3.1. 18 April 1998 , M=5.2, Epicentral Distance= 30 km

This event was recorded during a distinct coseismic deformation with the tiltmeter and extensometric recordings of the station Villanova, where 2 horizontal pendulums (EW and NS component) and 3 horizontal extensometers are installed (Braitenberg, 1999b). The recorded coseismic deformation is consistent with a dislocation model of the earthquake rupture (Braitenberg, 1999b). The linear prediction filter method is applied to a time interval from

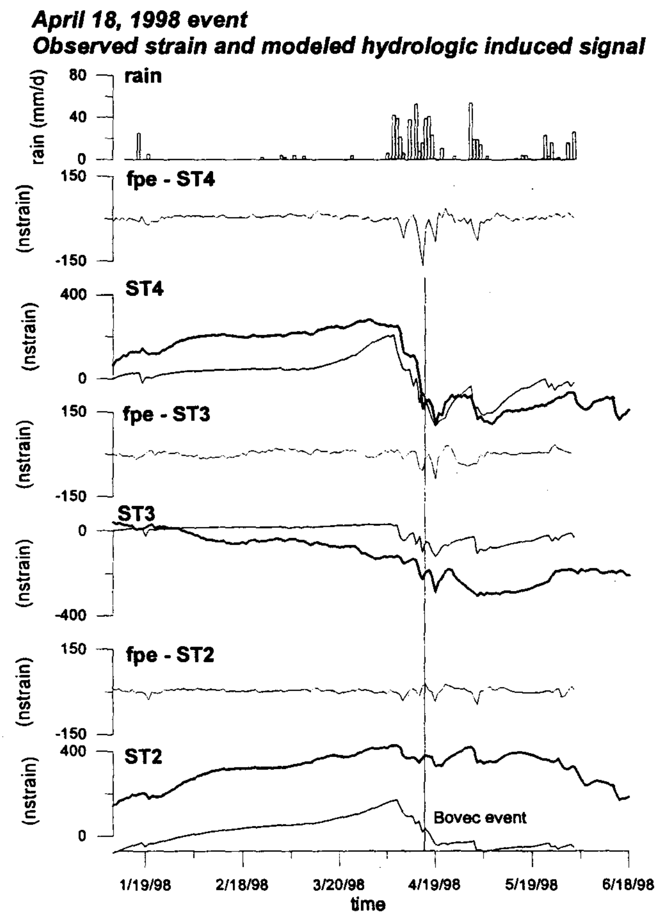

Fig. 1. The extensometer recordings (bold, extension positive) at station Villanova over a period of 6 months together with the modeled rain-induced signal (daily sampling). Also shown is rainfall and the forward- prediction- error (fpe). During this time period a major seismic event (Bovec, M=5.2) occurred at about 30 km epicentral distance from the station (vertical line).

January 1 to June 30, 1998. The extensometric records, reduced to daily samplings, are highpass filtered with cut-off period P=100d. The model order is chosen, that maximizes the correlation coefficient between fpe and rainfall. The maximum correlation coefficients and model orders for the three strainmeters were 0.56 and 2 for ST2 (α=N128E), 0.44 and 2 for ST3 (α=N27E), and 0.61 and 2 for ST4 (α=N67E), respectively. The observed extensometer recordings and the modeled hydrologic effect are shown in Figure 1, together with the rainfall and the fpe. The coseismic deformation is not seen in the data reduced to daily values. The time of the seismic event falls into a period in which the hydrologic induced deformation is quite strong.

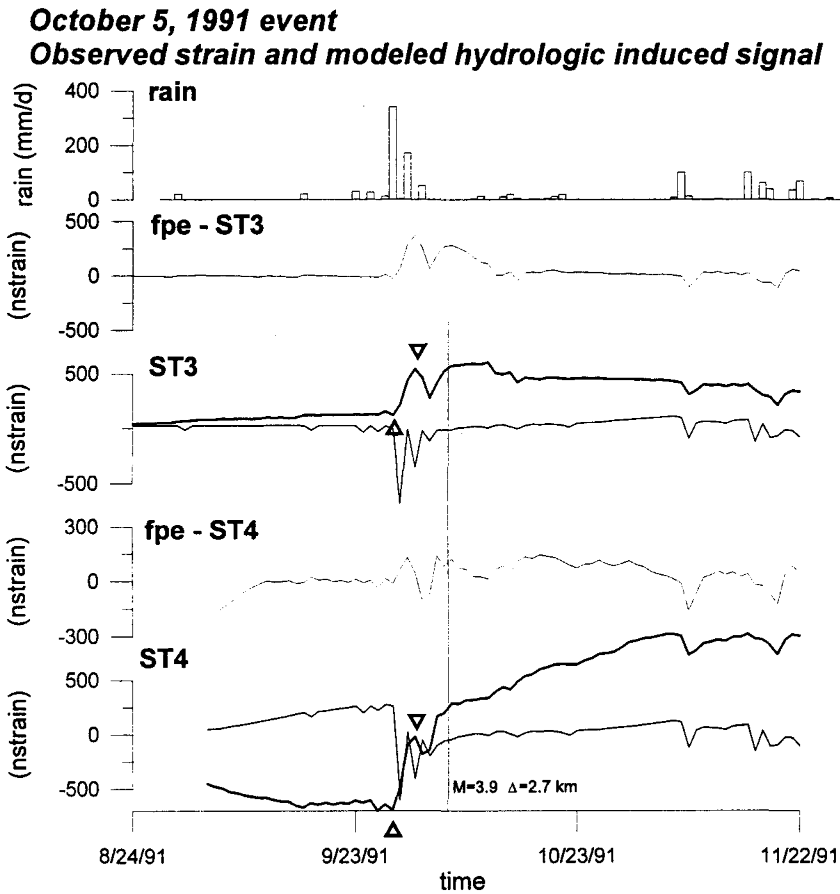

Fig. 2. The extensometer recordings (bold, extension positive) at station Villanova over a 3 months period together with the modeled rain-induced signal (daily sampling). Also shown is rainfall and the forward-prediction-error (fpe). In this case the deformation previous to the seismic event (identified by two triangles) is not explainable by the normal hydrologic induced signal.

3.2. 5 October, 1991 , M=3.9, Epicentral Distance=2.7 km

This event occurred at short distance to the station VI, and was observed by tilt- and strainmeters. A few days before the earthquake occurrence an anomalous signal was observed with two of the strainmeters (Dal Moro and Zadro, 1999). It is characterized by an extension of 400-500 nstrain of both instruments, and lasted for several days. The onset was contemporaneous with a very strong rainfall, but the deformation was extensional, instead of contractional, as the usual hydrologic induced signal. We apply again the linear forward prediction filtering and follow the procedure exposed above for determining the filter order. The observed and modeled signals are shown in Figure 2. It can be seen that the observed extension is anomalous with respect to the modeled deformation. The rain induced signal occurring in the beginning of November yields again good agreement between model and observation.

4. Conclusions

The hydrologic influence on deformation measurements is not negligible and should always be considered when interpreting the observations in terms of tectonic signals. We have used the method of linear predictive filters to investigate the induced deformation. A systematic study on eight years of extensometric measurements has shown that the hydrologic induced signal is irrelevant or masked by other effects of greater amplitude for variations with time scales greater than 4-5 months. We have applied the predictive filtering method to model the hydrologic induced signal in extensometric records and tilt measurements. It has been shown that the method helps to distinguish between hydrologic induced deformation signals and deformation signals of tectonic origin.

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