First annual progress report for DE-FG02-06ER15779

Monitoring the Subsurface with Multiple Scattered Waves and Quasi-static Deformation

Introduction:

We have been exploring a new technology that is based on using low-frequency strain attenuation data to monitor changes in fluid saturation conditions in two-fluid phase porous materials. The attenuation mechanism is related to the loss of energy due to the hysteresis of resistance to meniscus movement (changes in surface tension, wettability) when a pore containing two fluids is stressed at very low frequencies (< 10 Hz). This technology has potential applications to monitoring changes in (1) leakage at buried waste sites, (2) contaminant remediation, and (3) flooding during enhanced petroleum recovery

We have concluded a three year field study at the Maricopa Agricultural Center site of the University of Arizona. Three sets of instruments were installed along an East-West line perpendicular to the 50m by 50m irrigation site (see Figure 1). Each set of instruments consisted of one three component seismometer and one tiltmeter. Microseisms and solid Earth-tides served as strain sources. The former have a power peak at a period of about 6 seconds and the tides have about two cycles per day.

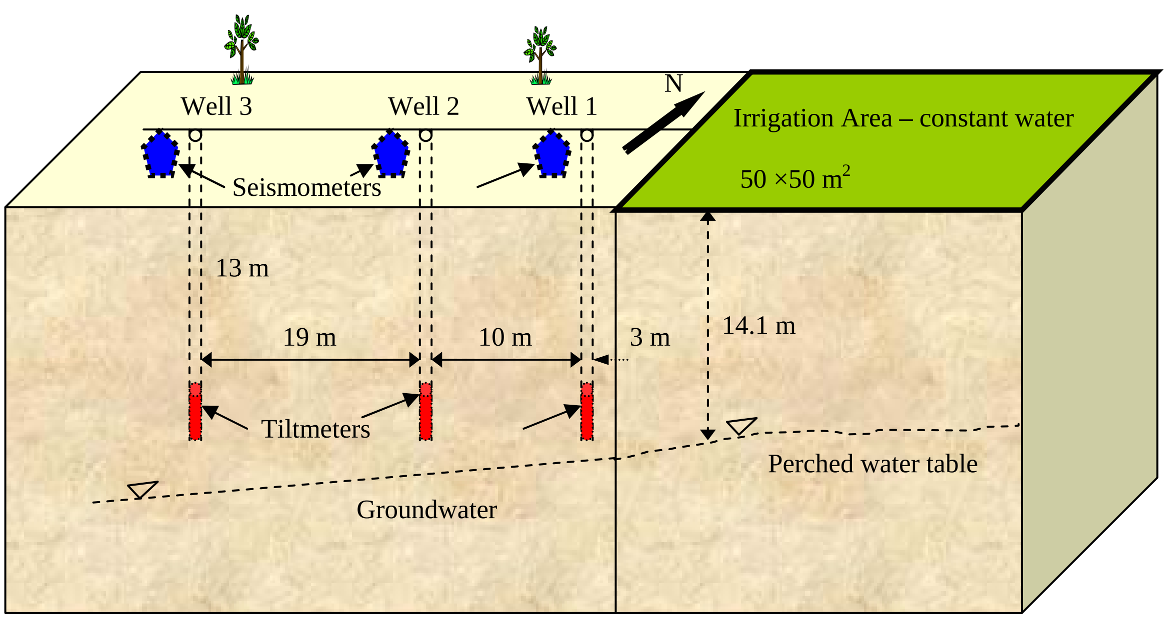
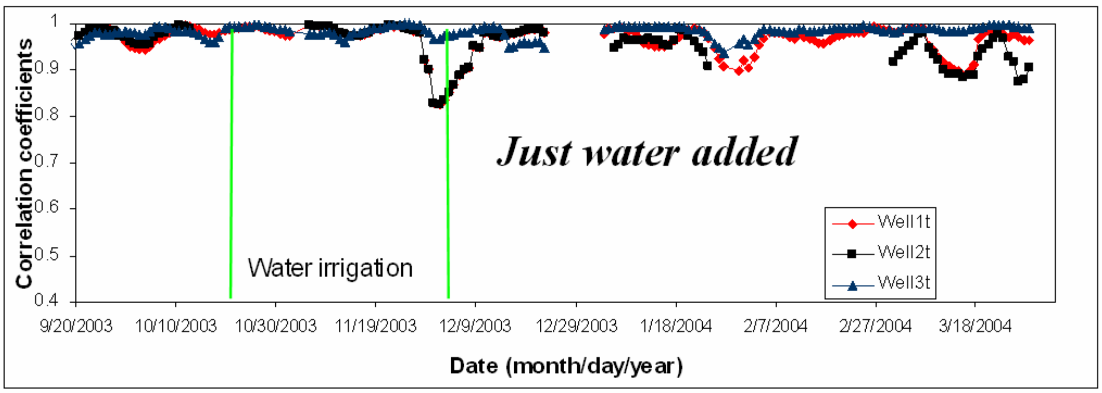


Figure 1. This schematic shows the field site in Arizona. The tiltmeters were installed at a depth of about 10m in cased holes. The seismometers were buried at about 1m.

Installation of instruments commenced in late summer of 2002. The instruments operated nearly continuously until April 2005. During the fall of 2003 the site was irrigated with water and one year later with water containing 150 ppm of a biosurfactant additive. This biodegradable additive served to mimic a class of contaminants that change the surface tension of the irrigation fluid.

Tilt data clearly show tidal tilts superimposed on local tilts due to agricultural irrigation and field work. When the observed signals were correlated with site specific theoretical tilt signals we saw no anomalies for the water irrigation in 2003, but large anomalies on two stations for the surfactant irrigation in 2004.



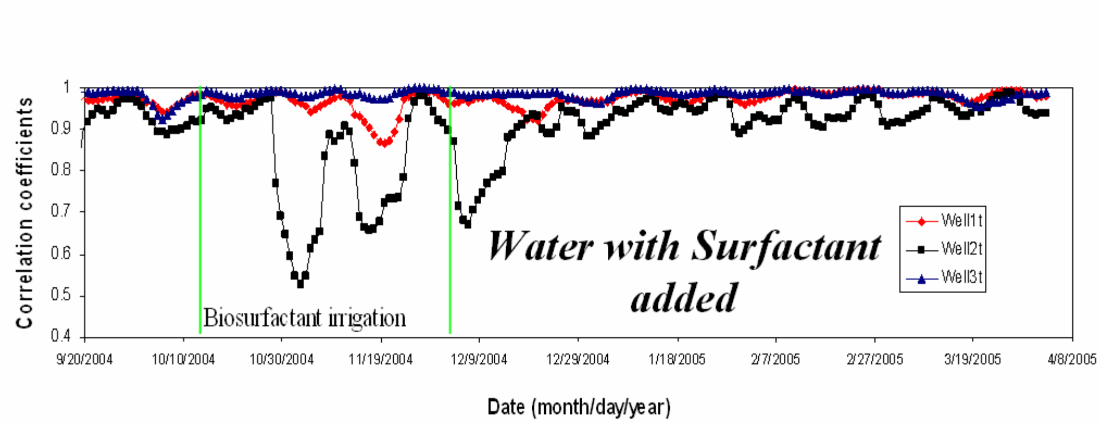


Figure 2. The correlation coefficient between theoretical tilt and measured tilt are shown. Considerable data analysis was required to get the measured data into a form that allowed the final correlation study.

Seismic Data:

Seismic data are noisier than the tilt data, but do also show possible anomalies for the irrigation with the surfactant. The quantity of data is large and we will analyze them after the tilt data have been thoroughly looked at.

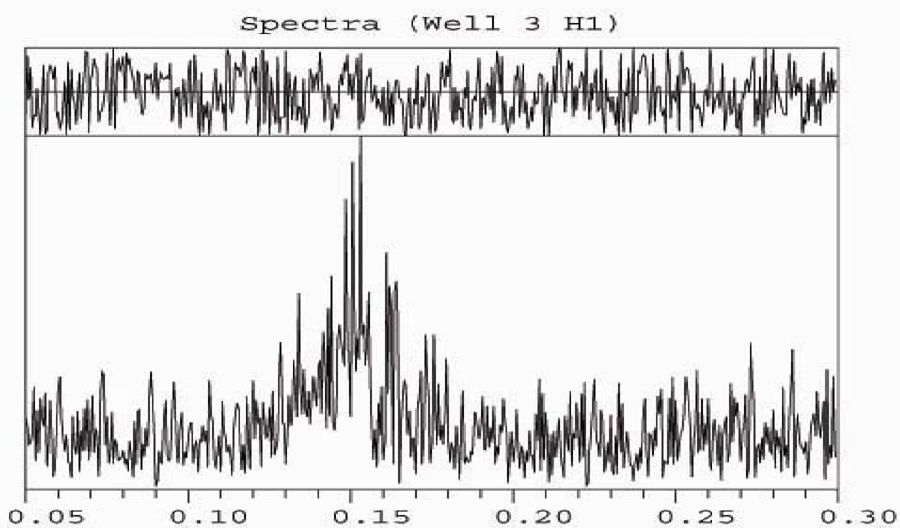
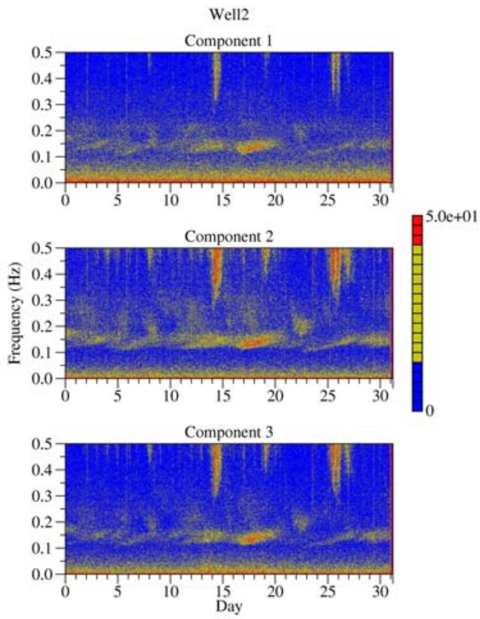


Figure 3. A spectrum from one of our wells in the frequency range from 0.05 to 0.3 Hz. The peak near 0.15 is due to microseisms with periods near 6 seconds.



Power in seismic signal for a one month period

Figure 4. Power spectra are shown for a one month period for the 3 components from the seismometer of Well 2. Note how the intensity of the microseisms (frequency around 0.15 Hz 0 varies.

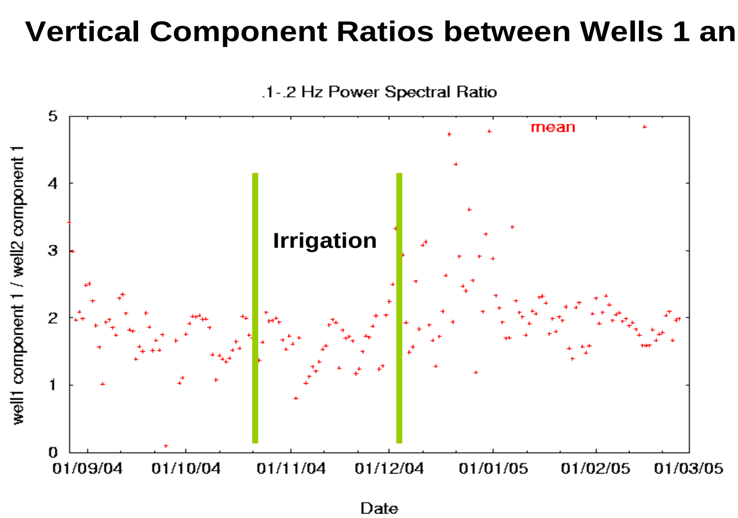


Figure 5. Power ratios are shown for the vertical components between well 1 and 2. Note the onset of what appears to be an anomaly several weeks into the irrigation with a surfactant. This anomaly disappears again several weeks after the irrigation ceases. For comparison look at the tilt data in figure 2.

Work on Tilt Data:

We are taking a new approach to analyzing the tilt data to see if the spectacular anomalies and their correlation with the surfactant irrigation hold or if they could possibly be artifacts of the previous analysis.

Preparing the measured data for analysis and comparison with the theoretically generated data requires a thorough understanding of the times (the time axes) at which the tilt readings were taken. Furthermore the noise, which is much larger than the signal, must be removed with only minimally affecting the phase and/or amplitude of the tilt signals. In the following we describe the work that has preceded the generation of 16 files that form the bases for further work.

When data were downloaded the quartz-clocks in the down-hole tiltmeters were reset to the time on the field-computer used for the download. We are examining all possible errors that could have resulted in incorrectly assigned times. Possible errors in the time axes could result from:

- Drift in the instrument clocks related to temperature changes.
- Drift in the instrument clocks related to quartz crystal aging.
- Constant drift in the instrument clocks related to inherent frequency error in the quartz crystals.
- Forgetting to synchronize the field computer before taking it to the field. This would result in incorrectly resetting the instrument clocks.
- Not resetting the tiltmeter clocks to the field-computer clock.

The above errors will contribute to time gaps on time axes whenever data are downloaded and the clocks are reset. The errors must be eliminated and/or the magnitudes of their contributions well known.

All original data were saved as they were downloaded from the instruments. We learned to understand sources of time gaps in addition to the ones above. Some were due to the time required for writing data blocks (164 data/block) onto the internal hard disk, some due to downloading those data blocks onto the external computers during data collection. The following table shows those time gaps that are associated with the downloading events for the East West component in the tilt data from Well 1 surrounding the fall of 2004.

All time gaps for well 1 are given for the 2004 irrigation data (azwell1_11_01-04_to_4_8_05.ptx or w1_04.mat). The ptx file has AZ time and the mat file GMT.

- **A:** time at start of time gap
- **B:** excess time in seconds (beyond the 75s which is the normal interval to the next datum) to the next datum. Negative time means that there were fewer than 75 seconds to the next datum.
- **C:** number of datum in the mat file.

- **D:** block number in ptx file where the gap starts. Start of the gap is always the last datum in the block.
- **E:** number of data in block.

	A	B	C	D	E	F
#	**Time and Date**	**Adj Sec***	**# in *.mat**	**Block # in ptx**	**# of data in block**	**comments**
1	25-Sep-2004 13:24:31	12	39597	242	73	Block 243 starts 12s + 75s later and has 1 datum
2	25-Sep-2004 13:25:58	747	39598	243	1	Block 244 starts 747s + 75s later and has 164 data
3	25-Sep-2004 17:03:25 Next datum @ 17:03:32	-68	39762	244	164	Block 245 starts 7 s later, thus 68s too early.
***	******************	****	******	****	****	***************
4	17-Oct-2004 18:24:55	447	65168	399	150	Block 400 starts 447 + 75 later and has 2 data
5	17-Oct-2004 18:34:52	664	65170	400	2	Block 401 starts 664 + 75 s later and has 164 data
6	17-Oct-2004 22:10:56	-20	65334	401	164	Block 402 starts 55 s later, thus 20s too early.
***	******************	****	******	****	****	***************
7	01-Nov-2004 21:52:51	711	82597	507	43	Block 508 starts 711s + 75s later and has 164 data
8	02-Nov-2004 01:29:42	-70	82761	508	164	Block 402 starts 5 s later, thus 70s too early.
***	******************	****	******	****	****	***************
9	30-Nov-2004 20:15:16	344	115913	711	24	Block 712 starts 344s + 75s later and has 1 datum
10	30-Nov-2004 20:22:15	714	115914	712	1	Block 713 starts 714s + 75s later and has 164 data
11	30-Nov-2004 23:59:09	-61	116078	713	164	Block 714 starts 14 s later, thus 61s too early.
***	******************	****	******	****	****	***************
12	16-Jan-2005 16:54:04	392	169874	1042	4	Block 1043 starts 392s + 75s later and has 1 datum
13	16-Jan-2005 17:01:51	669	169875	1043	1	Block 1044 starts 669s + 75s later and has 164 data
14	16-Jan-2005 20:38:00	-47	170039	1044	164	Block 1045 starts 28 s later, thus 47s too early.
***	******************	****	******	****	****	***************
15	26-Feb-2005 20:40:32	-40	217266	1332	164	Block 13333 starts 35s later, thus 40s too early.
16	27-Feb-2005 00:04:52	-46	217430	1333	164	Block 1334 starts 29s later, thus 46s too early.

We uploaded the date from the instruments to Matlab and performed cubic splines to produce data sets for all pertinent tilt files, i.e. all East-West as well as North-South for the three wells and for the two time periods from September 1 through the following January 31, starting in 2003 and 2004 respectively. Together with the respective theoretical files these are 16 files, each 44064 bins long at 300 second (5 min) intervals for a total of 153 days (9/1 until 1/31 of the next year).

Below we show examples where we compare measured signals with corresponding theoretically generated signals.

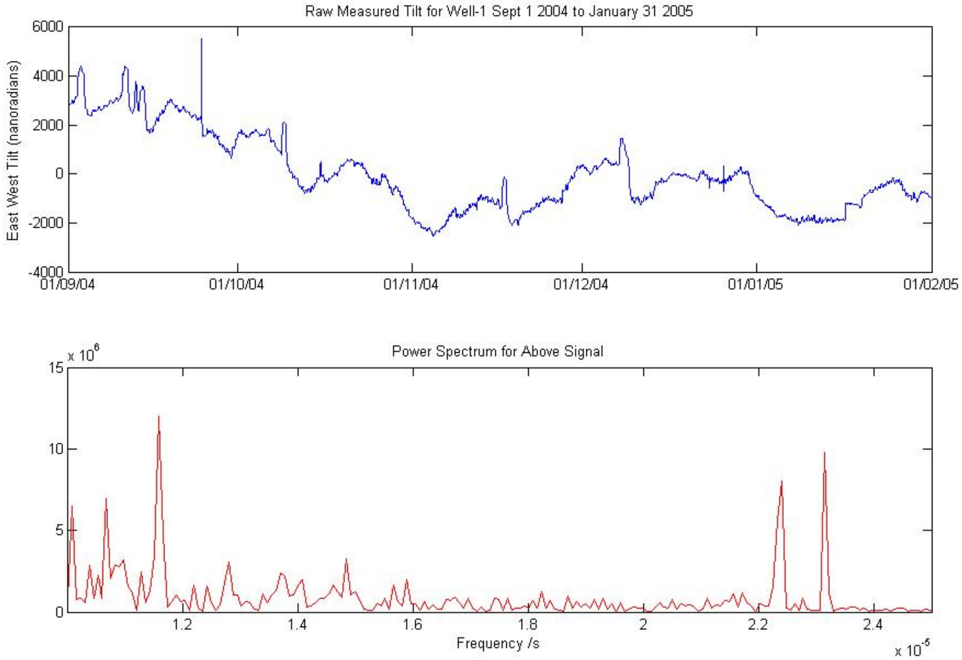


Figure 6. The top figure shows the 153 day long signal for the East West measured tilt for well 1 for the period from 1 September 2004 to 31 January 2005. This period includes the time during which the field was irrigated with a biosurfactant.

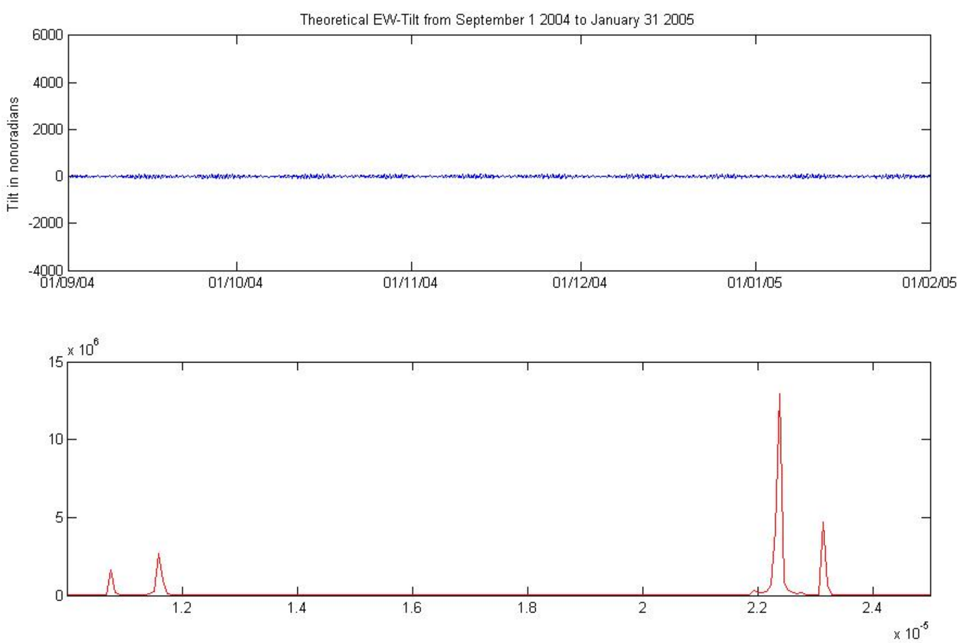


Figure 7. This figure corresponds to the above figure (figure 6), but is for the theoretical signal from the Earth tides only. We have chosen the same scale on the axes to emphasize the large back ground noise in the measured signal, when compared to the theoretical one.

When comparing the measured with the theoretical signal one notices the large background noise in the measured signal. We are able to identify much of the noise with pumping from deep wells for the irrigation of nearby fields and with ongoing construction. An FFT over the period of interest yields sharp peaks at the day and half day tidal periods (two right most peaks). See figure 8 below.

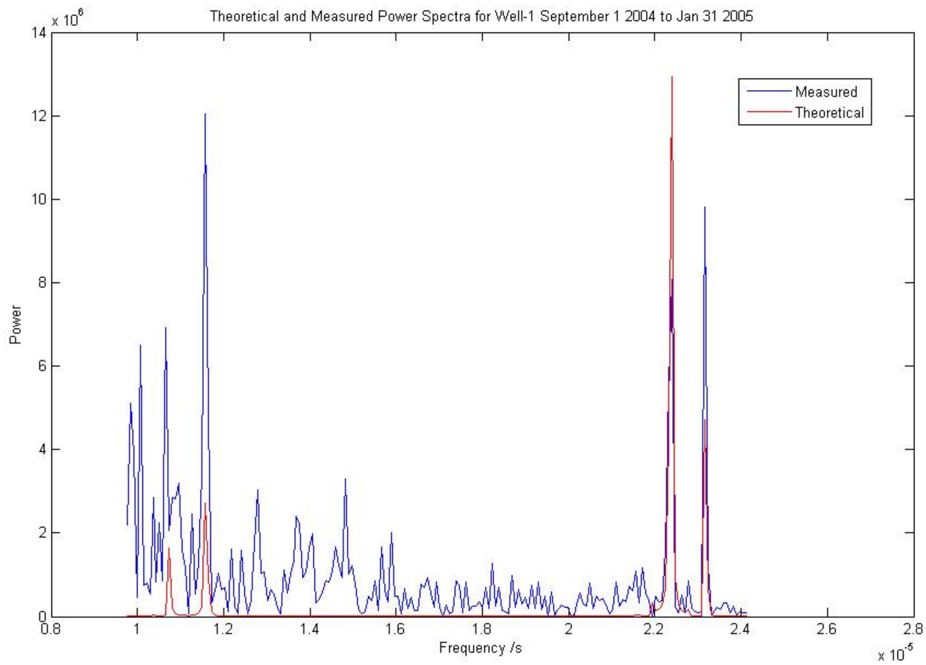


Figure 8. The spectra of the theoretical and the measured signals are plotted together The spectra show clearly that there is significant tidal energy in the measured signal, but the noise level especially for the full day tidal signals is considerable.

For close comparison of measured signals with each other and with theoretical signals we need to remove much of the strong low-frequency contribution. This is further illustrated in the following set of figures, figures 9 and 10.

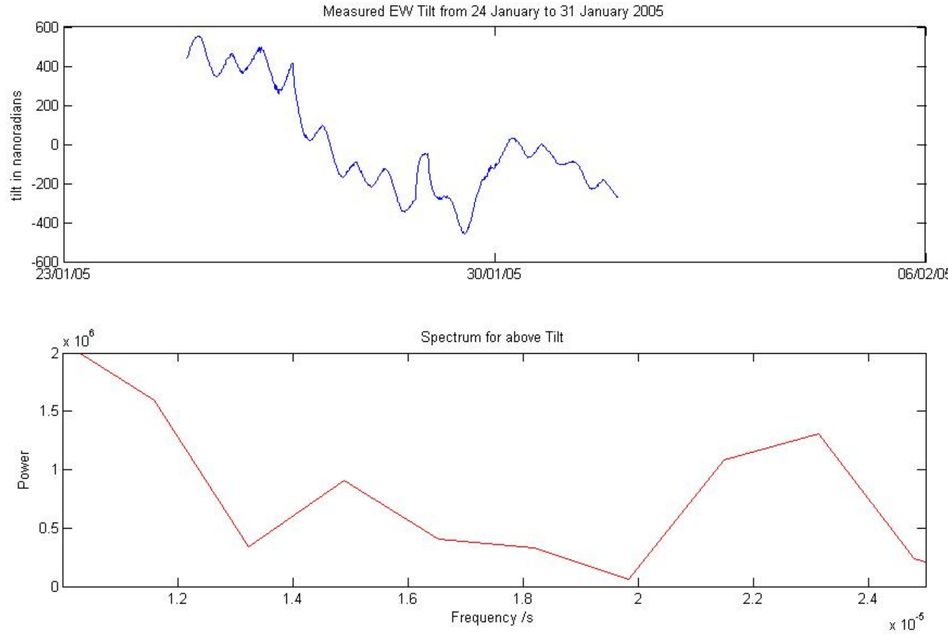


Figure 9. As above in figures 7 & 8, except that only 7 days instead of 153 days are used in the FFT.

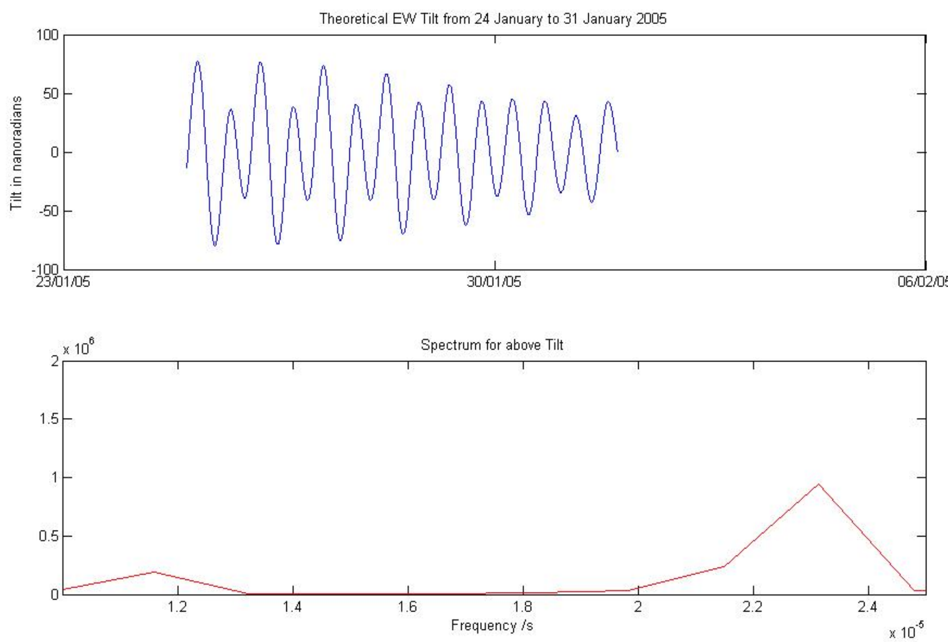


Figure 10. Same as figure 9, but for theoretical signal.

We need to compare the signals, theoretical and measured, with each other and see how the comparisons change during the two study periods.

We have explored some standard filtering techniques, but find that there is too much energy in the background noise to be able to extract a clean tidal component from the measured signal. We have started to piecewise detrend the measured signal with some success. This is tedious and requires utmost care. When piecewise fitting the signal with a low frequency function, it is important to have the endpoints at times when the tidal component is zero, otherwise there is a bias in the remainder, the tidal component. We (Hartmut Spetzler of CU, Boulder and Roel Snieder of CSM, Golden) are collaborating and are looking for sophisticated methods that allow us to subtract the background without compromising or biasing the tidal component of our signal.

Considerable effort was expended in creating the 16 files, mentioned above, which are now ready for signal processing. The time-correct joining of separately downloaded files was difficult and time consuming, especially when an instrument had to be retrieved from its down-hole location for repair.

The work that led to these 16 files is documented in many pages in a lab notebook and many Matlab programs. Some of the latter are still on file; others were erased during the extensive housekeeping that was associated with this work.

Instrument clock stability was studied and investigated in terms of the aging rate of quartz crystals and their temperature sensitivity. E.g. the maximum temperature excursions in the bore holes are less than 0.5 C during any of the pertinent time periods; temperature minimum occurs in early fall and maximum in early spring.

Work is continuing along the lines described above.