News from the Geodynamic Observatory Moxa: the 4-component borehole strainmeter

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Abstract

In September 2005 a 4-component borehole strainmeter was installed in a borehole inside the gallery of the Geodynamic Observatory Moxa, south of Jena, Germany. There, two quartz-tube strainmeters are recording along the two perpendicular axis of the gallery, as well as a laser-strainmeter connecting the end points of the quartz tubes. The borehole strainmeter comprises four strain gauges: three in the horizontal plane and one gauge for the vertical component. A fifth channel provides the temperature.

The strain sensor consists of a small magnetometer, the linear potentiometer FS-3791 invented by MACOME Corporation, Japan. The resolution of the strain sensors over the diameter of the sonde of 104 mm allows the detection of the tides as well as seismic signals with a high dynamic range. 1 µm corresponds to about 400 mV equivalent to 10^4 nstrain. Thus, the output signal of 1 mV equals 2.5 nm (~ 25 nstrain). The analog data is filtered and sampled every 10 seconds. The signal magnitude is in the order of some millivolts. Therefore the data is amplified by a factor of about 10, and the offset can be corrected before digitization. The first results presented here are promising.

Keywords:, borehole strain measurements, geodynamics, Geodynamic Observatory Moxa

1 Introduction

Continuous multi-component monitoring of crustal activities is the special field of co-author Hiroshi Ishii: He built several borehole devices comprising sensors for the monitoring of tilt, strain changes, seismic waves, magnetic field and temperature. Such instruments are installed in boreholes, the deepest drilled up to now being 1200 m (Ishii et al., 2003; Okubo et al., 2004; Asai et al., 2005). Thus, the design of the borehole sensor is adaptable to different tasks. The sonde provided for the Geodynamic Observatory Moxa consists of four strain sensors (three in the horizontal plain, one in the vertical), and a temperature sensor is suitable to monitor the conditions of the location (at the beginning especially the progress of hardening of the concrete to couple the sonde to the surrounding rock).

Besides other geophysical instruments, in the Geodynamic Observatory Moxa also three strainmeters are operating: These are two quartz-tube strainmeters (each 26 m long), oriented North-South and East-West, and one laser-strainmeter in a horizontal borehole (38 m) which connects the end points of both quartz-tubes to form a right angled triangle (Jahr et al., 2001; 2006). In the junction of the two galleries containing the quartz-tubes we drilled a 10 m deep borehole for the installation of the borehole strainmeter. To fix the strainmeter in the borehole an expanding cement is used. For Moxa observatory the provided borehole sensor comprises 3 horizontal strain sensors at different orientations (0°, 120°, 240°), a vertical sensor and a temperature sensor.

2 The borehole strainmeter: Sensor and calibration

The sensor consists of a mechanical sensor operating like a miniature fluxgate magnetometer. Fig. 1 shows a sketch of this device. It consists of a pair of magnets whose

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north and south poles are aligned opposite, such that a strong magnetic field gradient emerges (top left). The miniature sensor is given in the center and its orientation on the right. The travelling direction is up and down in parallel to the paper surface. The sketch below shows the perpendicular direction to demonstrate the importance of the alignment along the center, and the air-gap, crucial for the sensitivity and the resolution of the signal. The displacement is monitored by the relative movement between these magnets and a very small fluxgate magnetometer (Linear potentiometer FS-3791, MACOME Corporation, Japan).

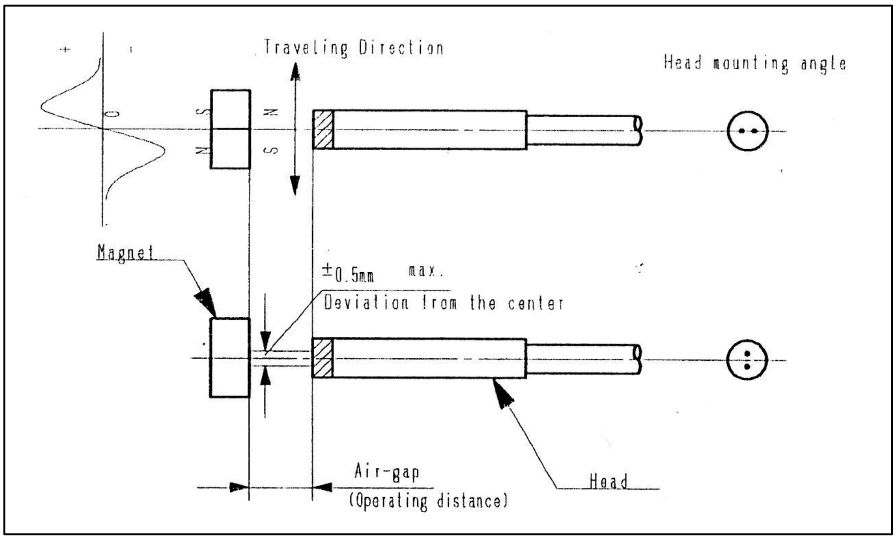
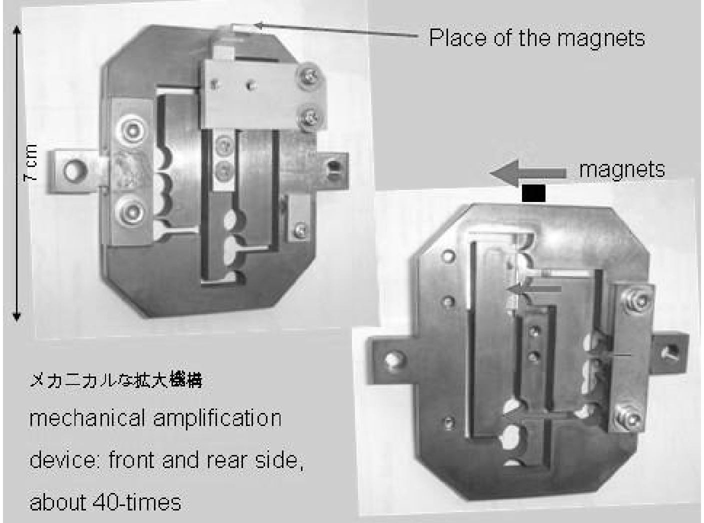


Fig.1. Sketch of the magnetic displacement read-out system (Linear potentiometer FS-3791 by MACOME Corporation, Japan; from the manual, courtesy by MACOME).

In order to increase the resolution a mechanical unit is used to amplify the deformation signal by a factor of about 40. Fig. 2 shows the mechanical amplifier. The displacement signal is fed into this plate and amplified in three stages due to the lay-out of the hinges.

The calibration function is determined in the laboratory. Fig. 3 shows one example.



メカニカルな拡大機構
mechanical amplification
device: front and rear side,
about 40-times

Fig. 2. Mechanical amplification device: Note the hinges which take care that the input deformation is amplified in several stages. Finally, the deformation is read out by the magnetic sensor.

Since the diameter of the borehole instrument is only 0.104 meter, the resolution of the magnetometers have to be very high. Fig. 4 shows a section of the calibration function of the sensor HS-3. The other three sensors have similar relations, but different offsets. The linear factor is the amplification factor which has to be multiplied with the amplification applied in the second step. The factor here is 370.7428 mV/µm, with a very small error of < 0.5 %. According to the calibration table of sensor HS-1 we have the relations:

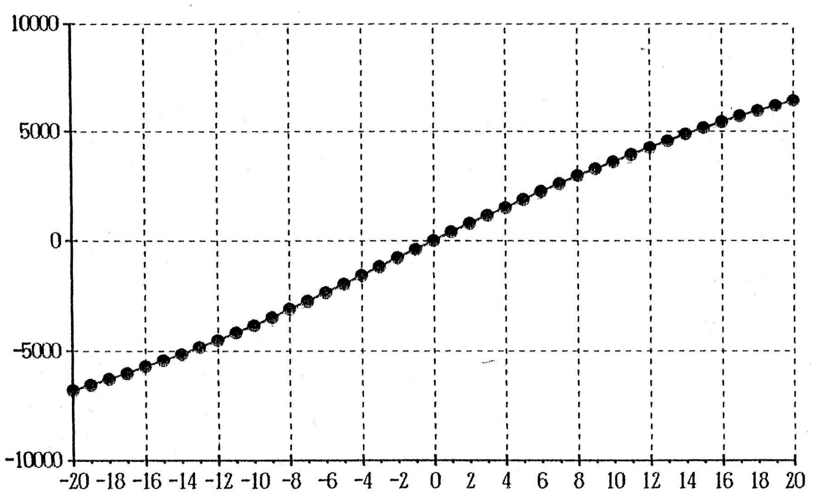


Fig. 3. Calibration function of one of the sensors (millivolts / vertical axis versus displacement / horizontal axis); note linearity around zero (from the manual, courtesy by MACOME).

1 µm	370.7428 mV	corresponding to	$0.96 * 10^4$	nstrain
1 mV	2.70 nm	corresponding to	27.0	nstrain

Since the strain changes to be observed are in the order of magnitude of about 50 nstrain it is clear that the calibration factor is not critical. But, before amplifying the signal for digitisation we have to determine its level and note the factor. If there is no strong drift over several micrometers (which is normally not to be expected) this factor can be used throughout.

In order to digitise the data we first apply analog filtering (anti-aliasing) with a cut-off of about 20 mHz. In this step we have the opportunity to compensate the offset, if necessary, and the signal is then amplified by a factor of about 10 (HS-1: 9.93; HS-2: 9.66; HS-3: 10.00; VS-1: 10.04). Then, we sample the data every 10 seconds using a HP34470A (Agilent, resolution 24 bit), multiplexing all four channels and the temperature channel. In addition we also record one of the strain outputs directly for comparison.

The whole sonde has a length of 1.22 meters. It comprises of four sections: At the bottom is a weight to reduce buoyancy, two sections contain the horizontal and the vertical strain sensors, respectively, and one section on the top contains the electronics and the temperature sensor. The borehole has a diameter of 150 mm, and a depth of 10 m. Actually, the borehole was drilled more than two meters deeper, but an inclining fault was detected, and, thus, it was decided to fill it with concrete up to the installation depth of 10 m. The installation was carried out such that a rod was fixed to the top with a mark indicating the orientation. Later, the borehole was filled with an expanding cement mixed according to a special recipe. The strainmeter was pressed into the fluid cement, and the orientation was kept by turning the rod accordingly. Finally, it was oriented such that channel HS-1 points towards east.

Although the cement was filled up to the top of the borehole, its volume was reduced during the drying out time. Now, we have about 2 meters between the top of the cement and the gallery floor which can be used to calibrate the strainmeter by taking out and/or filling in water.

2 Data and first results

It took about four weeks for the cement to dry out, which was monitored by the temperature and the strain changes. Fig. 5 gives the data for the first period, September 12 until

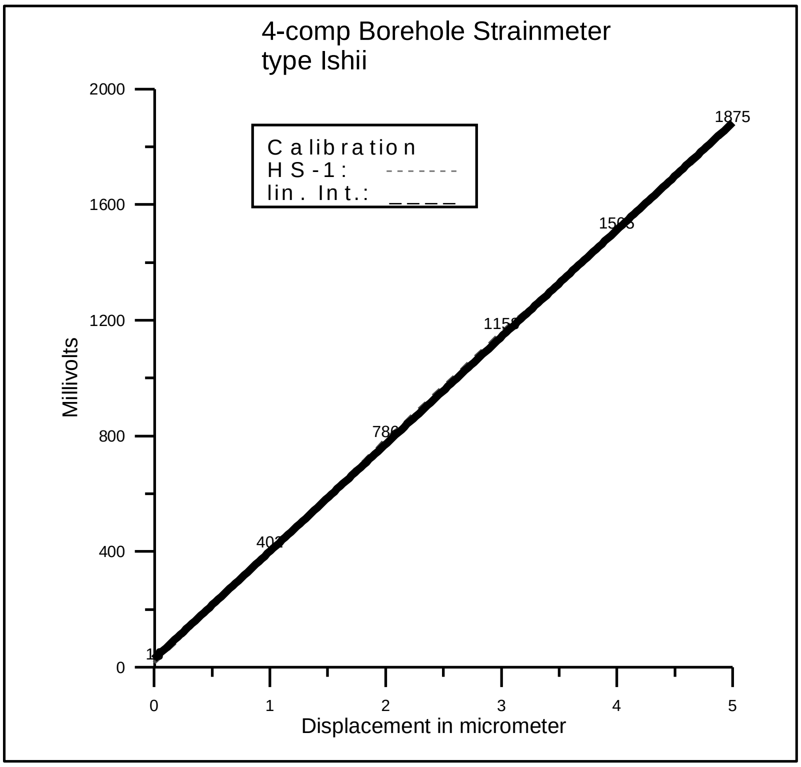


Fig. 4. Calibration function of horizontal sensor HS-1: This function is determined in the laboratory. The deviation to linearity is very small, and the factor is determined by linear interpolation. The numbers at the curve denote the voltage outputs obtained at the displacements in steps of one micrometer.

November 4, 2005. During this period we recorded with a reduced resolution of 10 percent to avoid the data going off scale. Thus, the amplitude scales (on the left) have to be multiplied by a factor of 10. The scale on the right denotes the temperature in degree devided by 10: The temperature of the rock is about 7.5° Celsius. The reasons for the two small steps are unknown.

Fig. 6 shows a section of the data of channel 2 (SH-2) pointing 210°, November 24 until December 10, 2005. The output in volts has to be converted to nanostrain using the calibration provided in the manual. The tides are clearly visible, as could be expected. The recording unit used now amplifies the signal by a factor of about 10.

3 Discussion

The borehole strainmeter runs in parallel with the above mentioned quartz-tude strainmeters and the laser strainmeter. Therefore, it is most interesting to compare the observed borehole strain with these long-based instruments. As a first example of this comparison we show a spectrum of both East-West components (Fig. 7). For this comparison we used a section of 33 days, filtered the data to hourly samples and computed the spectra. The time interval is February 5 – March 9, 2006. Both spectra are calibrated and the amplitudes can be compared directly. As can be seen, the noise levels are about the same, especially in the long-period part, but the tidal amplitudes are a little different.

Since the calibration is still preliminary and has to be verified, it is obvious that the diurnal tidal amplitudes are of the same order of magnitude and fit quite well. In contrary, the semi-diurnal amplitudes are quite different. Since the East-West strain is very sensitive against changes in orientation we assume that the azimuth determined by adjusting the rod fixed to the strainmeter may not be as accurate as intended. We will check the orientation by comparison of tidal analyses with the theory and with the other three strain components.

Table 1 contains the comparison of the first tidal analyses of both record sections. The results for the individual tidal constituents confirm the findings from the spectra. The obtained noise levels as well as the standard deviation are of the same order of magnitude.

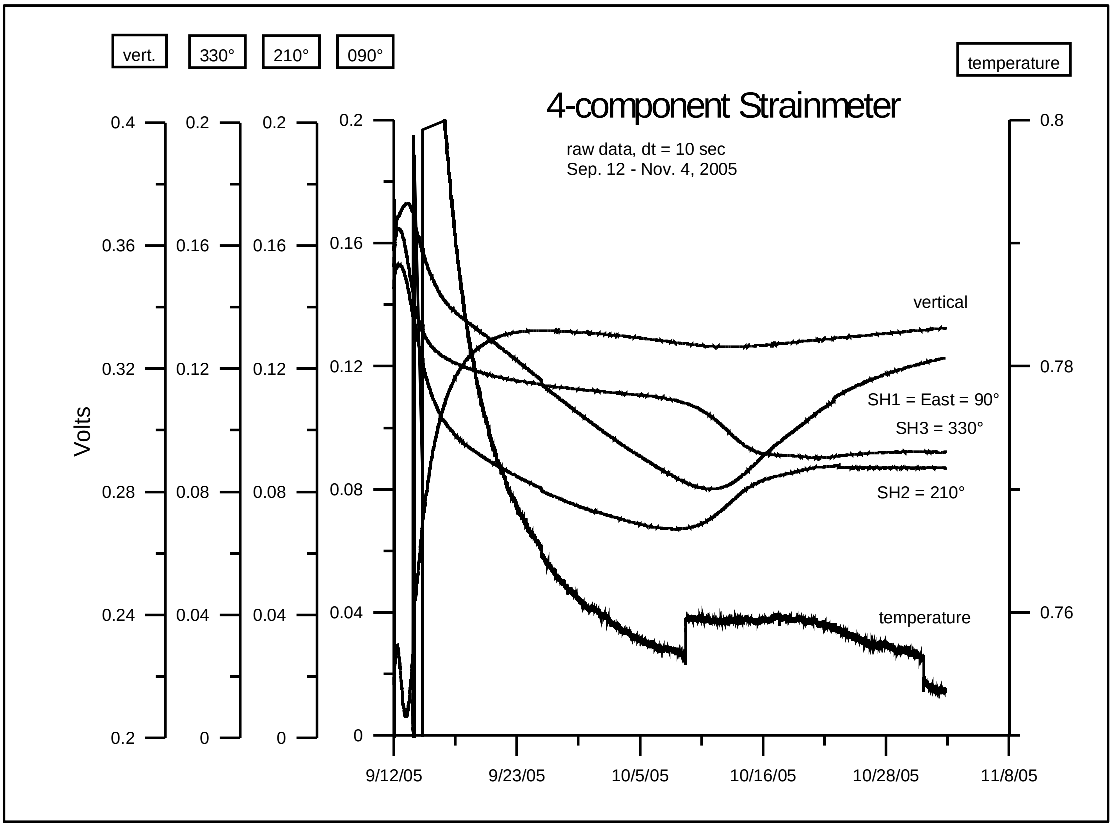


Fig. 5. Data for the first period, September 12 until November 4, 2005, recorded with a reduced resolution; note the running-in period. The temperature scale must be multiplied by 10 to give degrees Celsius.

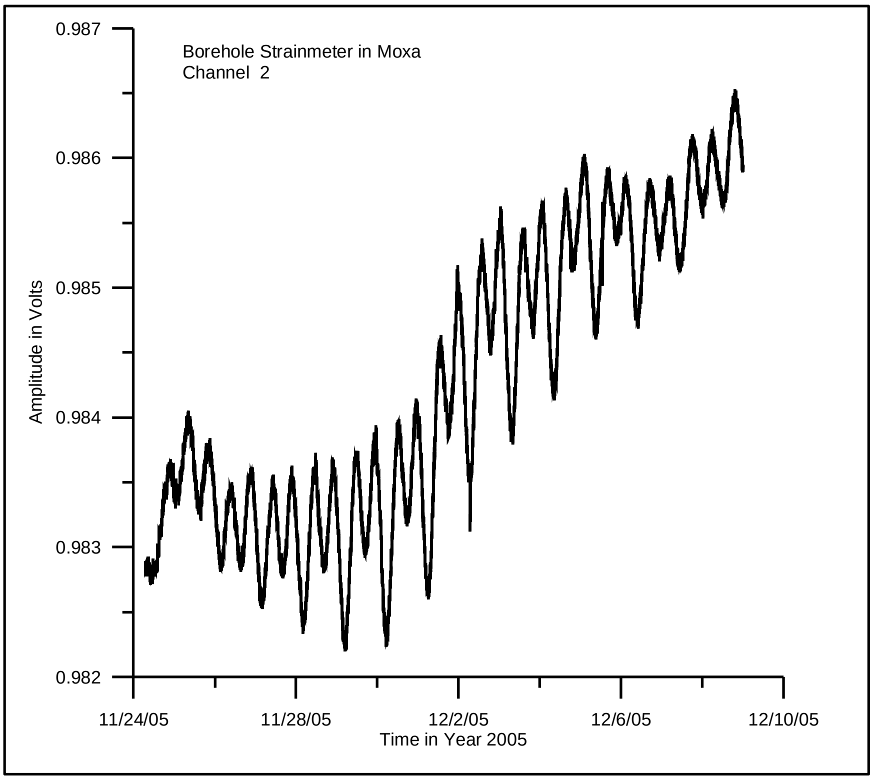


Fig. 6. Data of channel 2 pointing about 210° (South-West to North- East); the period is November 24 until December 9, 2005, now recorded with full resolution.

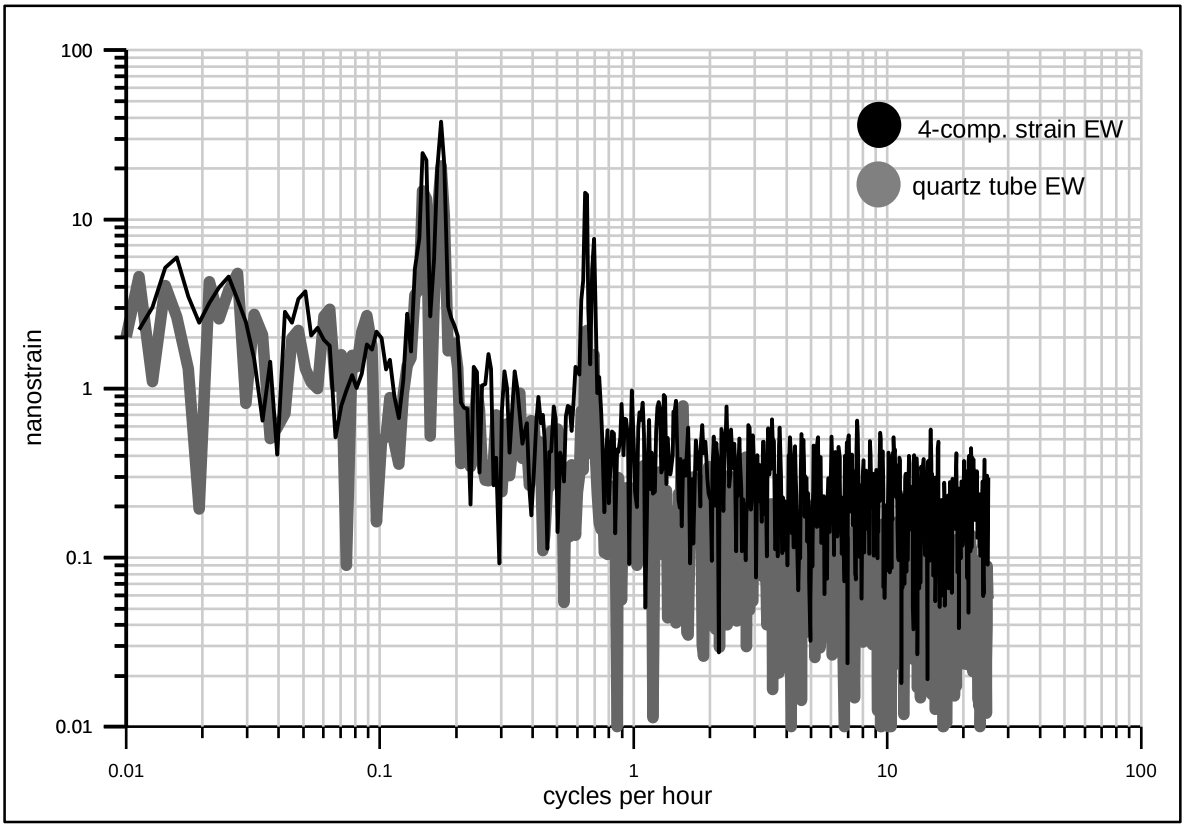


Fig. 7. Spectra of the strainmeters in direction EW: SH-1 and quartz-tube, hourly values, 33 days: Feb. 5 – March 9, 2006; note the good correlation in the low-frequency part (see text).

Acknowledgments

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Table 1. Comparison of computed tidal parameters for the East-West components of the borehole strainmeter and the quartz-tube strainmeter; note differences in the amplitudes of the semi-diurnal constituents (period: 68 days, January 1 until March 9, 2006). The analyses were carried out using the program ETERNA 3.3 (Wenzel, 1996).

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Borehole strainmeter, component SH-1 (East-West)

Estimation of noise by FOURIER-spectrum of residuals

0.1 cpd band  99.9990  nstr   1.0 cpd band    0.1292  nstr
2.0 cpd band    0.0777  nstr   3.0 cpd band    0.0701  nstr
4.0 cpd band    0.0533  nstr   white  noise    0.0768  nstr

adjusted tidal parameters :

             ampl.    ampl.fac.  stdv.     ph.   lead       stdv.
             [ nstr   ]                          [deg]      [deg]

Q1           0.7935   0.60310  0.03786     10.0495    3.5969
O1           4.3631   0.63493  0.00843      6.6419    0.7603
M1           0.5025   0.93031  0.07620     17.9806    4.6931
K1           5.9721   0.61820  0.00596      5.5735    0.5526
J1           0.3829   0.70855  0.09666    -34.7265    7.8164
OO1          0.2196   0.74317  0.11900    -11.8649    9.1745
2N2          0.1496   7.37131  1.45881    179.6032   11.3390
N2           0.6748   5.31177  0.33323   -156.1341    3.5944
M2           3.2057   4.83151  0.06347   -158.0459    0.7527
L2           0.0896   2.84154  0.74624    151.3012   15.0468
S2           1.2938   4.19151  0.11877   -160.1042    1.6236

Degree of freedom:                 1493
Standard deviation:                1.098   nstr
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Quartz-tube strainmeter (East-West)

Estimation of noise by FOURIER-spectrum of residuals

0.1 cpd band  99.9990  nstr   1.0 cpd band    0.1370  nstr
2.0 cpd band    0.0410  nstr   3.0 cpd band    0.0676  nstr
4.0 cpd band    0.0553  nstr    white  noise    0.0721  nstr

adjusted tidal parameters :

             ampl.    ampl.fac.  stdv.     ph. lead        stdv.
             [ nstr   ]                    [deg]           [deg]

Q1           0.8454   0.64253  0.04248      3.5051    3.7880
O1           4.5574   0.66321  0.00938      0.8582    0.8099
M1           0.4674   0.86525  0.08549    -17.3093    5.6611
K1           5.7250   0.59262  0.00654     -0.0039    0.6327
J1           0.4303   0.79627  0.10789     11.2228    7.7635
OO1          0.2555   0.86436  0.13454      5.6552    8.9180
2N2          0.0562   2.76907  0.82147    -88.6306   16.9974
N2           0.2348   1.84849  0.18576    126.7215    5.7578
M2           0.8525   1.28481  0.03518   -175.5750    1.5688
L2           0.0579   1.83529  0.41173    160.1035   12.8538
S2           0.4860   1.57465  0.06670   -106.1775    2.4270

Degree of freedom:                 1555
Standard deviation:                1.108   nstr
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