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1 **Relations between microbarograph and strain data**

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7 **Abstract**

8 The relationship between barometric and strain data related to seasonal characteristics within
9 a year was studied on the basis of parallel records from a quartz tube extensometer and a
10 microbarograph at the Geodynamical Observatory in Sopronbánfalva, Hungary. Both strain
11 and barometric data series were combined into groups according to the three 'Lloyd' seasons
12 and they were subjected to spectrum, tidal, regression and coherence analysis. All of the
13 analysis methods establish long periods, with seasonally varying relations between
14 atmospheric pressure and linear deformation measurements in the tidal frequency band. We
15 found that the separate seasonal barometric correction of the strain data did not bring a
16 notable improvement in the diurnal band, while in the semidiurnal band the improvement was
17 about 10% better than correcting the whole year's data in a single step.

18 **Keywords:** Atmospheric pressure; Barometric correction; Coherence analysis; Strain; Tidal
19 analysis

20 **1. Introduction**

21 Atmospheric loading is one of the major factors that effects extensometric measurements by
22 loading and deforming the Earth's surface. Barometric pressure variations have a complex
23 influence on this kind of measurement, which means that the changes of atmospheric pressure
24 on the whole Earth contribute to local deformations at any point on the Earth's surface. The
25 pressure changes cause a direct deformation of the Earth's solid crust; they also have an

26 indirect effect by changing the ocean loading. In addition atmospheric pressure variations take
27 place in a wide timescale from seconds to years. Most papers deal with the effect of
28 atmospheric pressure variations on gravimetric measurements, and therefore most authors
29 investigate only the radial displacement of the Earth's crust (e.g. Sun, 1995; Kroner and
30 Jentzsch, 1999; Boy et al., 2006). The effect of barometric pressure variations on
31 extensometric measurements was less intensively studied, than the effects on gravimetric
32 measurements. However the high sensitivity (better than 10^{-10} strain) of the extensometers
33 makes it possible to use them for investigation of the Earth's interior. The barometric pressure
34 induced "noise" may limit the extraction of very small signals of interest, e.g. long periodic
35 tides, resonant elastic deformations of the Earth's crust, etc. Farrel (1972) computed
36 deformation caused by surface load. Rabbel and Zschau (1985) investigated the deformations
37 and gravity changes on the Earth's surface due to regional and global atmospheric pressure
38 variations in the case of a spherical radially stratified Earth. It was found that the principal
39 horizontal strains may have amplitudes up to 10^{-8} and $\pm 1.5 \cdot 10^{-9}$ for seasonal changes in the
40 atmospheric pressure distribution. Van Dam and Wahr (1987) calculated the time dependent
41 effects of global atmospheric pressures on surface point positioning measurements and on
42 gravity observations. They found that the displacements and gravity fluctuations were
43 somewhat smaller during summer than winter months. Probably this is why the existing
44 barometric pressure reduction methods can only be used with a limited accuracy for
45 correction of strain data. Another problem is that the removal or reduction of barometric
46 disturbing signals from strain data series is much more difficult than with gravimetric
47 measurements, since the barometrically induced strain also depends on the properties of the
48 bedrock and on the topography in the vicinity of the observatory. This was investigated by
49 comparing the atmospheric pressure effects on a surface and a deep station by Mentés and
50 Eper-Pápai (2006). In the last decade some papers studied the attributes of disturbed strain

51 signals due to atmospheric pressure variations (e.g. Onoue and Takemoto, 1998). Among
52 others, Kroner et al. (2005) and Steffen et al. (2005) investigated the physical transfer
53 mechanism between the barometric pressure and strain changes by finite element modelling.
54 At the Geodetic and Geophysical Research Institute (GGRI) of the Hungarian Academy of
55 Sciences, some methods for removal of the barometric pressure variations from strain signals
56 were also studied (Mentes, 2000; Eper-Pápai and Mentes, 2002). Since the regression method,
57 – together with other methods (see also Kroner and Jentzsch, 1999) – was not effective
58 enough to eliminate the atmospheric pressure effect from strain measurements, the aim of the
59 present research is to study the seasonal properties of the effects of atmospheric pressure
60 variations on strain measurements using extensometric and local atmospheric pressure
61 records. In this paper the seasonal features of the barometric pressure, and relationships
62 between air pressure and strain data were investigated by spectrum, tidal, regression and
63 coherence analysis.

64 **2. Observations and data pre-processing**

65 The Sopronbánfalva (a suburb of Sopron) Geodynamical Observatory in Hungary is located
66 on the Hungarian Austrian border in the eastern foreland of the Alps. Its coordinates are:
67 latitude $47^{\circ} 40' 55''$ N; longitude $16^{\circ} 33' 32''$ E; height is 220 m a.s.l. The observatory is an
68 artificial gallery driven into gneiss. The depth of the gallery is about 60 m (see Fig. 8). A
69 much more detailed description of the observatory is given by Mentes (2005, 2008). In 1991 a
70 22 m long quartz tube extensometer with an azimuth of 116° was installed in the gallery about
71 30 m from the entrance. The displacement of the free end of the extensometer is measured by
72 a differential capacitive transducer. The instrument is calibrated daily by a built-in
73 magnetostrictive actuator (Mentes, 1991). In 1997 a highly sensitive (0.0024 hPa/mV)
74 microbarograph was developed at the GGRI for studying atmospheric tides (Mentes, 2004).
75 This instrument is installed separately from the extensometer in a room about 10 m from the

76 entrance and 20 m from the extensometer. In addition to strain and atmospheric pressure
77 measurements, the inside and outdoor temperatures were also recorded. In the observatory the
78 yearly and daily temperature variations are less than 0.5 °C and 0.05 °C, respectively. We did
79 not find any correlation (correlation coefficient was 0.03) between the microbarograph, the
80 strainmeter and the inside temperature data, so the direct effect of temperature on the
81 instruments can be disregarded. In the middle of 2001, a high resolution 24 bits digital
82 voltmeter was installed for digitizing extensometric, barometric and temperature data. For the
83 sake of the uniform data series, we used only the data recorded between 2002 and 2006 in our
84 investigations. They were collected with a sampling rate of one sample/minute and were
85 filtered by the equipment's built-in anti-aliasing filter. To get one value per hour the data
86 series were resampled by the decimate routine of the ETERNA 3.30 tidal analysis program
87 (Wenzel, 1996). Data series were also filtered by a high pass filter, with a cut-off frequency
88 of 0.8 cycles/day, before processing. For the strain analysis in the diurnal and semidiurnal
89 tidal bands, K1 (P1K1 group) and S2 waves were chosen because the K1 lunisolar diurnal
90 wave has about the same magnitude (58.4 percent of the magnitude of M2) as the S2 principal
91 solar wave (46.6 percent of the magnitude of M2). According to K1 and S2 waves, the
92 atmospheric tidal waves S1 and S2 were chosen for the barometric pressure analysis.

93 **3. Investigation of the seasonal relationship between barometric pressure and strain** 94 **data**

95 **3.1. Barometric pressure variation**

96 We calculated the monthly averages and standard deviations of the hourly atmospheric
97 pressure data in each year to study how the magnitude of the atmospheric pressure changes
98 depends on the seasons. To present the variation of the barometric pressure in a simple way,
99 the average of the standard deviations was calculated for each month of 2002-2006. These
100 averages and their standard deviations are presented in Fig. 1. It can be clearly seen that the

101 barometric pressure variations (average line) and their standard deviations (SD line) are
102 higher from October to April than from May to September.

103 **3.2. Spectrum analysis**

104 We determined Fourier amplitudes in the frequency range of K1 (P1K1) and S2 strain and S1
105 and S2 barometric waves in each month of the period we investigated to inspect the yearly
106 behaviour of the tidal waves regarding both strain and air pressure measurements. Figure 2
107 represents one typical amplitude spectrum for both strain and pressure data. The spectral
108 amplitudes were determined with an accuracy of about 0.25 nstr for deformation, and about
109 0.013 hPa for pressure data. Since only records of single months were subjected to spectrum
110 analysis, those tidal waves which are close to each other in frequency (P1 and K1) cannot be
111 separated and an annual periodic amplitude variation results. The theoretical strain tides for
112 the same geographical location were calculated and monthly spectral amplitudes were
113 determined and applied for correction of the amplitudes from the strain data. A simple
114 subtraction was made between the measured and the theoretical amplitudes. This diminished
115 the temporal tidal amplitude variations. Figure 3 presents the results of spectrum analysis
116 obtained for the year 2006. Calculations in other years show similar a tendency. In Fig. 3 the
117 measured and theoretical data amplitude differences (meas.-theor.), the barometrically
118 corrected measured and theoretical data amplitude differences (correct.-theor.) and amplitudes
119 from the measured pressure data (barog.) are delineated for both the diurnal and semidiurnal
120 frequency bands. The barometric correction was completed by means of the regression
121 method separately in each year in the investigated period. On the basis of the results obtained
122 for 2002-2006, we found that in the semidiurnal band the amplitude difference changes are
123 smaller than in the diurnal band, as shown in our example in Fig. 3. We ascertain from these
124 results that in the diurnal band, the correction of the barometric effect did not cause a marked
125 decrease of differences between corrected and theoretical amplitudes. Barometric correction

126 of deformation data seems to work moderately in the semidiurnal band where we observed a
127 somewhat evened amplitude course of the corrected data.

128 **3.3. Tidal analysis**

129 Through the following calculations we examined tidal parameter relationships on the basis of
130 the seasonal characteristics of air pressure, due to the global pressure system variations. Both
131 extensometric and barometric data were classified into seasonal groups, according to the three
132 'Lloyd' seasons denoted by "D", "E" and "J" months for tidal and regression analysis
133 (Chapman and Lindzen, 1970). D months are: November, December, January and February
134 (centred on the winter solstice); J months are: May, June, July and August (centred on the
135 summer solstice) and E months are: March, April, September and October (centred on the
136 equinoxes). This grouping takes the similar weather conditions and barometric pressures into
137 consideration for the investigations. Tidal parameters were calculated by means of the
138 ETERNA 3.30 tidal analysis program (Wenzel, 1996) using the Wahr-Dehant Earth model
139 (Wahr, 1981; Dehant, 1987). Calibrated atmospheric pressure data was subjected to the
140 analysis as a gravitational component, giving adjusted amplitudes in the original physical unit.
141 In the tidal model, amplitude lines around only S1 and S2 waves were applied. Yearly data
142 series (2002-2006) were constructed for the tidal analysis according to the seasonal groups.
143 Each yearly data series begins on 1st of November of the previous year and ends on 31st of
144 October of the actual year, e.g. the data series year 2002 is: 01.11.2001-31.10. 2002. In each
145 year (2002-2006), the amplitudes of the K1, S2 strain and S1, S2 barometric tidal waves were
146 separately calculated in the D, E and J months by the ETERNA 3.30 program. Averages of
147 the five amplitudes in each group was determined, and presented in Fig. 4. Figure shows
148 clearly that the larger the amplitude of the diurnal barometric wave S1 is the smaller the
149 amplitude of the corresponding strain wave K1. Changes in the semidiurnal band (def_S2 and

150 \bar{S}_2) are much smaller than in the diurnal band, and changes in the opposite direction are
151 not so pronounced as in the diurnal waves (def_{K1} and \bar{S}_1).

152 **3.4. Regression analysis**

153 Regression coefficients were calculated between the strain and atmospheric pressure data
154 series, taking the strain values as a function of the pressure data. Calculation of the regression
155 coefficients was carried out on individual year data and on seasonal segments of the series.

156 Standard deviation of the coefficient's determination varies randomly between 0.1-0.3
157 mstr/hPa . Results are shown in Fig. 5. In our former publication (Mentes and Eper-Pápai
158 2006), the phase relationship between deformation and air pressure in tidal frequency bands
159 were investigated, and no phase shift was detected in the Sopronbánfalva Observatory.

160 Regression coefficients were separately calculated for March, April and September, October
161 in the E months' group, and their averages were calculated (E months' average). There is a
162 large difference between coefficients obtained for March, April and September, October.

163 Coefficients of D months and E months' averages differ slightly from the yearly coefficients,
164 especially in 2004-2006. J months' values are smaller than the others, and they reflect the fact
165 that variation of the atmospheric pressure is smallest in summer.

166 We compared the Fourier amplitude spectra of residual data series after tidal analysis of both
167 corrected and original strain data, to examine whether seasonal correction of strain data yields
168 better results than applying a yearly based linear regression correction. No significant
169 amplitude decrease was found in the diurnal tidal band compared to the one year data
170 processing, which makes the efficiency of seasonal correction questionable. However in the
171 semidiurnal band residual amplitudes decreased by 20-30 % when seasonal groups are
172 applied, and this is 10% improvement against the one year processing. Results from residual
173 inspections agree with Fourier amplitude investigations in Section 3.2 to some extent, as there
174 we found a slight amplitude improvement only in the semidiurnal band.

175 **3.5. Coherence calculations**

176 Coherence analysis was also used to control the efficiency of the regression correction. First
177 we computed coherence between theoretical tide as the input signal, and the uncorrected
178 strain data as the output signal. The coherence function describes the mechanical and electric
179 transmission of our observatory instrument system. Next the computation was repeated using
180 the corrected strain data as the output signal. The results obtained for 2005 are shown in Fig.
181 6. We obtained similar curves for all of the years we investigated. The coherence value in the
182 semidiurnal band is very nearly 1, in contrast with the diurnal band where it is 0.8 without
183 correction. The suppressed transmission in the diurnal band is in accordance with our former
184 tidal results (Mentes and Eper-Pápai, 2006).

185 In the diurnal band the efficiency of the correction is somewhat better than in the semidiurnal
186 band. In spite of this fact, the coherence value is smaller than 0.9. It means that either the
187 correction is not effective enough in this frequency band or there are other disturbing effects.
188 Mentes (2002) investigated the effect of temperature variations on deformation data as a
189 possible source of noise, though in that work the long term changes were taken into account
190 without considering tidal frequencies. In the present study we made some comparisons using
191 coherence analysis, taking such data series as output signals, corrected for both pressure and
192 temperature. The resulting coherence values coincide with the barometrically corrected data,
193 and no improvement was found. Our other investigations show that the close phase
194 relationship between temperature and pressure components harden the separation of the
195 different effects.

196 **4. Discussion**

197 Barometric pressure variation and average barometric pressures are smaller in the summer
198 months than in the others (Fig. 1). The situation is the same in the regression coefficients
199 which are also somewhat smaller in J months than in D and E months (Fig. 5). This feature of

200 the regression coefficients can be more clearly seen in Fig. 7. In this Figure the average
201 regression coefficients, the average amplitudes (determined by tidal analysis) of the
202 barometric waves S1 and S2 obtained for D, E and J months (in 2002-2006) are given for
203 each month. Regression analysis shows that the changes of the regression coefficients along
204 with the variations of the barometric pressure beside a seasonal periodic change also have a
205 random variation.

206 Spectrum analysis shows the semidiurnal band is less disturbed by barometric pressure
207 variations than the diurnal band. Regression correction also gives better results in the
208 semidiurnal band which is supported by both the spectral amplitude values in Fig. 3 and the
209 residual analysis after tidal calculations. The magnitude of the variations of barometric
210 pressure in the diurnal band is about three times higher than in the semidiurnal band. Monthly
211 amplitude changes of the strain waves are opposite to the amplitude changes of barometric
212 waves in both tidal bands, although it is not obvious at first sight in the semidiurnal band
213 (Figs. 3 and 4). Coherence calculation gives the same results. These findings can be explained
214 by the topography of the observatory. Figure 8 shows the cross section of the surroundings of
215 the observatory constructed from the digital terrain model in the axis of the extensometer. The
216 instrument is perpendicular to the high steep rock face and is about 30 m from it, so the
217 changes of the barometric pressure cause large strain variations in the direction of the
218 extensometer (horizontal arrow in Fig. 8), while the horizontal deformation caused by the
219 vertical pressing force (vertical arrows) can be neglected. The situation is also confirmed by
220 the fact that the tempestuous blasts of wind appear in the extensometric data records, since the
221 steep rock face is perpendicular to the prevailing wind.

222 The resulting opposite change of the barometric pressure amplitudes relative to the values of
223 the regression coefficients requires explanation which we suppose is in the characteristics of

224 the topography and properties of the rock (inhomogenities, clefts, faults, etc.) near the
225 observatory. Further investigations are needed to reveal the reasons for this phenomenon.

226 **5. Conclusions**

227 Our investigations brought some new results which aim to improve barometric pressure
228 correction for linear deformation measurements. Seasonally completed regressional correction
229 yields better results than taking a whole year data series. There is about a 10% improvement
230 in the semidiurnal band and no improvement in the diurnal band. However, tidal parameters
231 can be determined with higher accuracy from long continuous data series. Further difficulty
232 arises with seasonal air pressure correction for strain data, since there will be jumps at the turn
233 of the seasons and they should be handled in data processing.

234 Analysis results show different behaviour of seasonal barometric corrections in the main tidal
235 bands. This raises the need for finite element modelling of our observatory's surroundings to
236 thermal and pressure disturbance investigations.

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240 maintenance of the instruments. We thank Walter Zürn and Thomas Jahr for the thorough
241 review of the manuscript which helped to improve this paper.

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289 **Figure captions**

290 **Fig. 1.** Average variability of the barometric pressure in different months of 2002-2006 (1
291 January to 12 December)

292 **Fig. 2.** Typical amplitude spectra for measurement data (April 2006)

293 **Fig. 3.** Monthly spectrum amplitude differences of strain and theoretical strain (meas.-theor.),
294 corrected strain and theoretical strain (correct.-theor.) as well as amplitudes of barometric
295 waves (barog.) in the diurnal and semidiurnal bands in 2006

296 **Fig. 4.** Average of the amplitudes obtained for D, E and J months from 2002 to 2006

297 **Fig. 5.** Regression coefficients between barometric and strain data

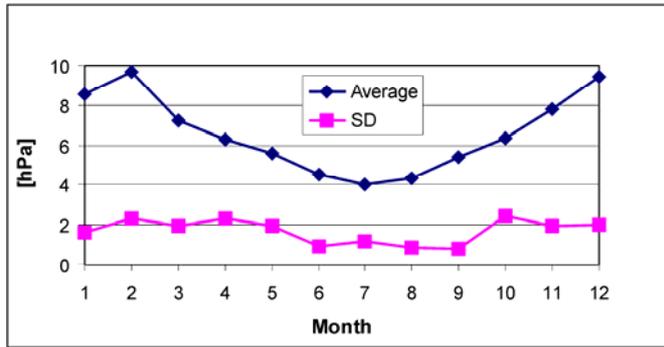
298 **Fig. 6.** Coherence between the theoretical tide and the uncorrected and barometric corrected
299 strain data

300 **Fig. 7.** Average regression coefficients and tidal amplitudes of air pressure data from 2002-
301 2006 for each month

302 **Fig. 8.** The cross section of the surroundings of the observatory made from the digital terrain
303 model in the axis of the extensometer. The azimuth of the cross section is 116° .

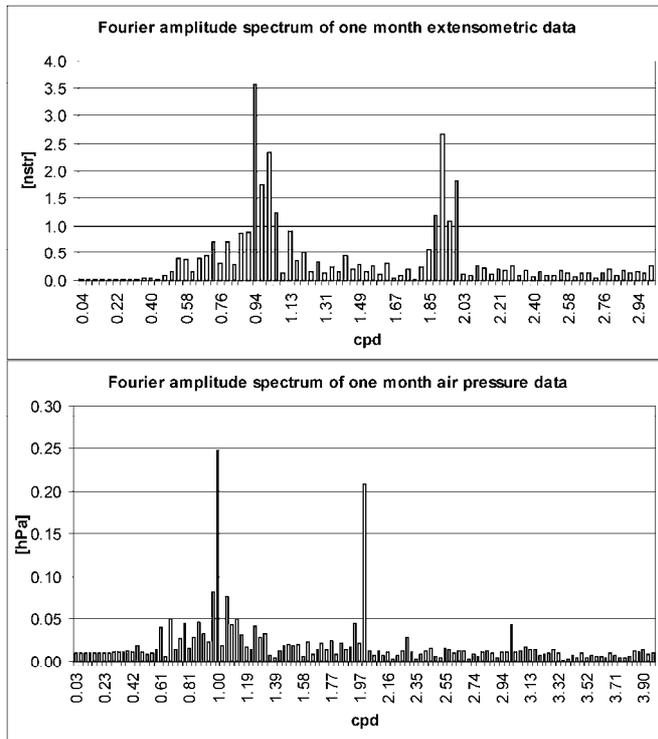
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Figures



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306

307 **Fig. 1.**

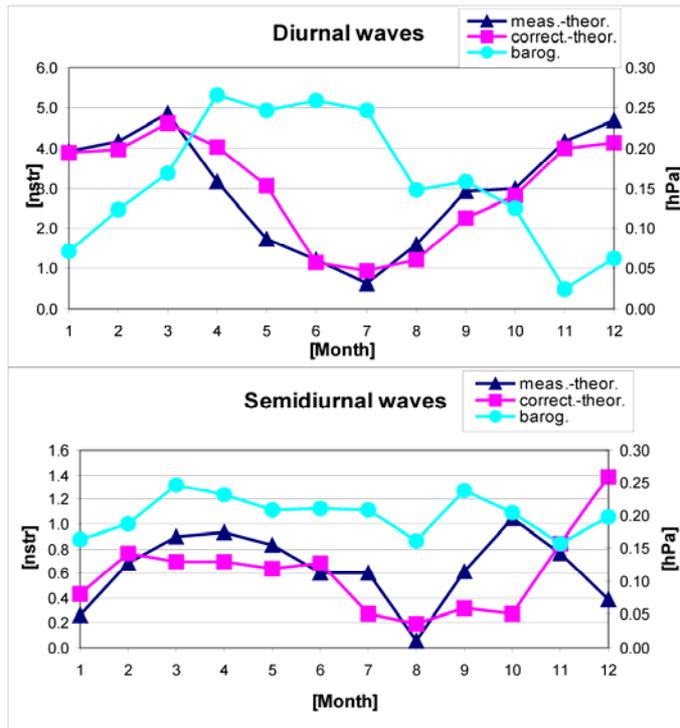
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311 **Fig. 2.**

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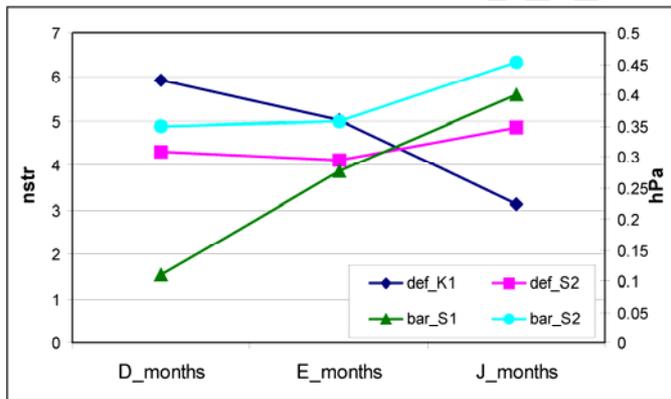


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314 **Fig. 3.**

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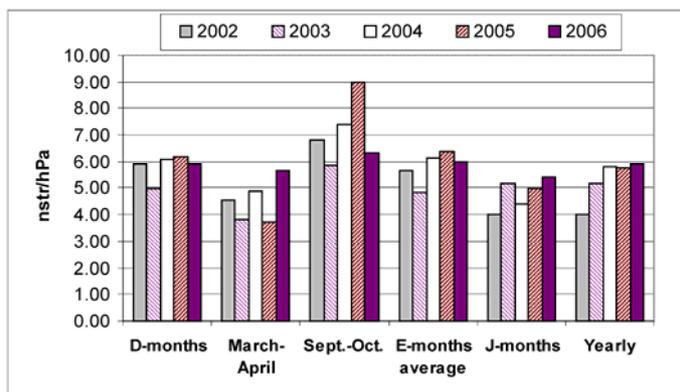


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318 **Fig. 4.**

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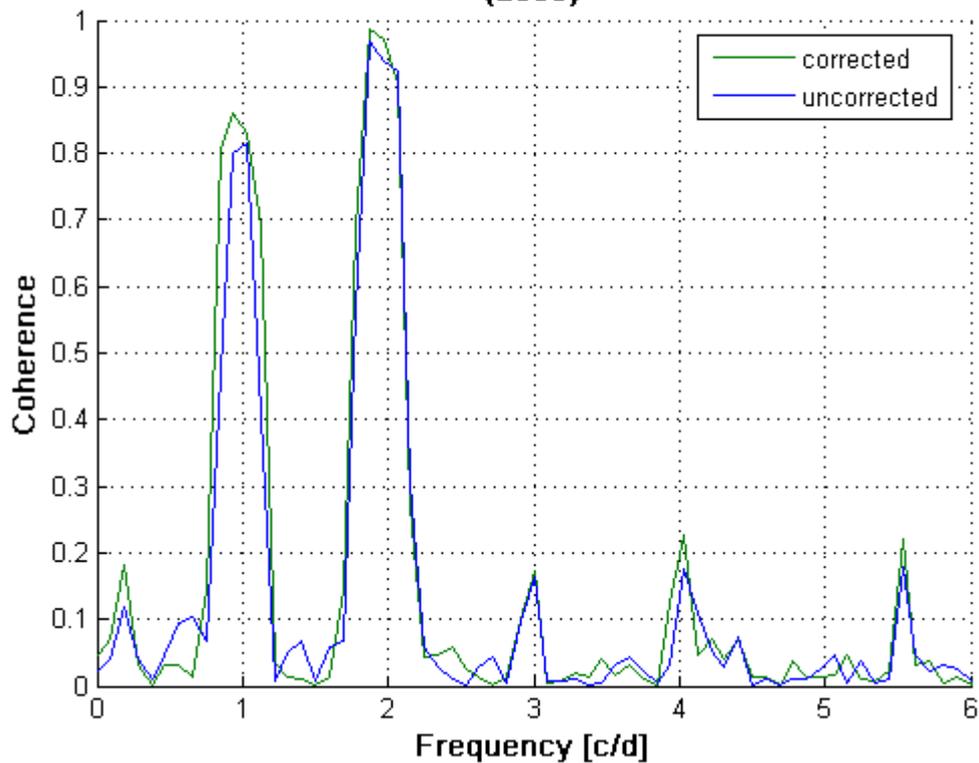
323 **Fig. 5.**

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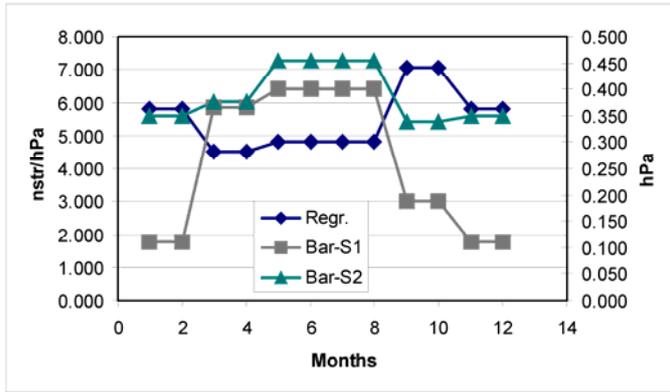
Coherence between theoretical and air pressure corrected strain data
(2005)



327

328 **Fig. 6.**

329

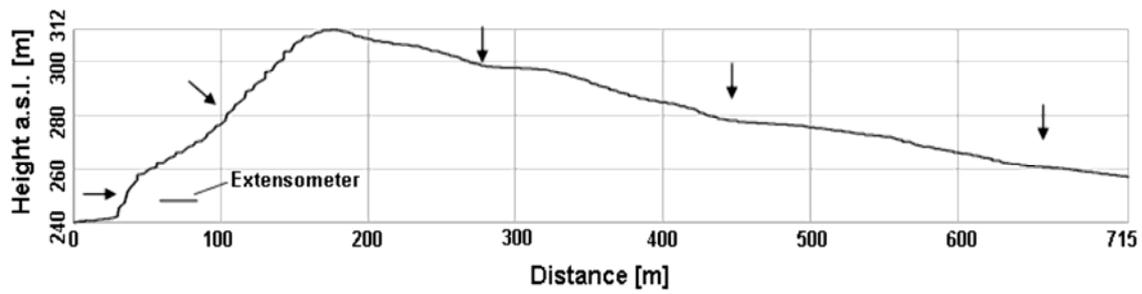


330

331 **Fig. 7.**

332

333



334

335 **Fig. 8.**

336