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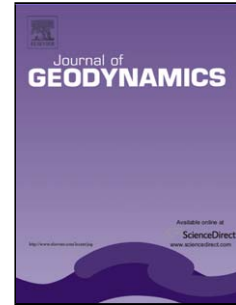
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1 **Oceanic loading monitored by ground-based tiltmeters at Cherbourg (France)**

2

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16

17

17 **Abstract**

18 We installed two orthogonal Blum-Esnoult silica tiltmeters in an underground military facility
19 close to the shore in Cherbourg (France). They have recorded the ocean tide and the
20 associated oceanic loading effects from March 2004 to July 2005. The signal to noise ratio is
21 such that, within a period range from a few minutes to a few days, the main nonlinear oceanic
22 tides up to the M10 group can be observed. The modelling of the tidal tilt deformation has
23 been carried out using oceanic models of the FES2004 family, with a stepwise refinement of
24 the grid size based on the unstructured grid T-UGAm model leading to the NEA-2004 tidal
25 solution. This improvement permits to reduce the discrepancy between the model and the data
26 with respect to the use of FES2004 alone, and show that, although the misfit remains
27 significant, one progresses toward an independent mean to validate the oceanic models and
28 finally the whole modelling process. We also show that tiltmeters open new opportunities to
29 explore loading of non linear tides on a larger spectrum than gravimeters and GPS do.

30 **Keywords**

31 Inclinometry, tilt, oceanic loading, FES2004, nonlinear tides

32 **1. Introduction**

33 The oceanic loading phenomenon involves the attraction and deformation of the Earth that are
34 due to the varying weight of moving water masses in the oceans and seas, mainly the oceanic
35 tides. These effects may be measured on the ground by several geodetic observables:
36 classically gravity, land level displacement, (Llubes *et al.*, 2001, Vey *et al.*, 2002, Llubes *et*
37 *al.*, 2008), but also strain (Beavan, 1974) and more rarely stress (see for instance Willcok,
38 2001).

39 This paper is focused on the tilt effects generated by tidal oceanic loading on the French
40 coast (Cherbourg, Cotentin region). The ocean tidal amplitude may reach there up to several
41 meters.

42 While considering gravity variations in the vicinity of a sea with large tides, the proper
43 loading contribution can reach about one third of the elastic earth tide variation (Llubes et al.,
44 2001). Tilts are much more sensitive to the coastal loading since the lateral gradient of
45 vertical displacement is involved measured rather than the amount of displacement, and the
46 gradient reaches its maximum close to the coast. Actually the loading tilt itself reaches at
47 Cherbourg about three times the solid tide tilt effect. Precisely, two factors converge to
48 generate a large amplitude to the loading tilt locally: 1) the decreasing rate of the tilt Green
49 function as a function of the load distance is more rapid with respect to gravity: the decreasing
50 of the tilt Green function is close to and asymptotically as $1/r^2$ instead of $1/r$ in the gravity
51 case (see for instance Farrell, 1972). This feature leads to a sort of homothetic invariance
52 scale (Rerolle *et al.*, 2006) when integrating over an area which also depends on r^2 ; 2) Coastal
53 areas are zones where the tidal amplitude is much greater than in the open ocean. Finally,
54 these properties make the tiltmeters highly sensitive and suitable to study local loading
55 phenomena.

56 Strictly speaking, tiltmeters record the variations of the gravity direction, more precisely the
57 variations between the instantaneous geoid and the crust on which these instruments are
58 settled. Both are affected by water loads. In practical terms, the only signal that can be
59 measured is the difference between the geoid and the crust. It is not possible to refer tilts to a
60 space or terrestrial reference frame because the accuracy that would be required to refer tilt
61 data to this frame should be of the same order of magnitude than a tiltmeter resolution (at
62 least), that is better than 10^{-9} rad at a few second time scale. Comparatively a one meter
63 diameter zenithal telescope would have a 10^{-6} rad resolving power. Of course, it is only a

64 practical limitation. Actually, the zero instrumental reference is just its initial state when
65 beginning the record.

66 The geometrical and dynamical effects induced by the oceanic loads can be easily computed
67 using the Green formalism (LLubes and Mazzega, 1997), which degenerates in a simple
68 convolutive formalism as long as the Earth is considered as spherically symmetric. One
69 specific Green function exists to describe the linear elastic Earth response to a local load in
70 terms of, respectively, vertical and horizontal displacements, stress, strain and gravity. Green
71 functions are available for different Earth models. We use here the functions devoted to tilts
72 provided by Pagiatakis (1990) which are relative to a viscoelastic, rotating PREM-like Earth.
73 (See also Boy *et al.* in this issue).

74 **2. Experiment description and site corrections**

75 **2.1. Tiltmeters records**

76 The tiltmeters used in this experiment are very compact instruments historically designed by
77 Blum (1962) (see also Saleh *et al.*, 1991) and nowadays built by Marie-France Esnault at
78 IGP. These instruments are made with silica glass and are built according to Zöllner's
79 pendulum concept. Tiltmeters require a two-step calibration: the first one is electronic (the
80 sensitivity of the displacement probe) and the second one is purely mechanistic (the
81 amplification of a pendulum is $1/\sin(\alpha)$, α being the angle between the rotation axe and the
82 vertical line). Scientific and historical background of this kind of probes may be found in
83 Melchior (1983). Braitenberg and Zadro (1999) also provide a suitable summary of their
84 functioning.

85

86 The tiltmeters used in this experiment can reach a resolution of about 10^{-9} rad (Saleh *et al.*,
87 1991). Actually the gain accuracy (calibration constant) is expected to be better than 4 % at
88 1σ . However, pendulums are affected by some “external” limitations. They are highly
89 sensitive to very local environmental background variations: temperature, dampness of the
90 floor where the instrument lies, and any kind of deformation of the stand. Generally speaking,
91 a noticeable drift is observed on that kind of instruments, which is rarely understood in
92 details. This drift could also involve the creeping of the tiltmeter components themselves: 10^{-9}
93 rad variation over a 30 cm baseline is $0.3 \cdot 10^{-9}$ m that is less than the elementary quartz crystal
94 size. Hence, a suitable efficiency can only be reached thanks to exceptional settling
95 conditions. In our experiment, two orthogonal pendulums have been installed in an unused
96 part of a military underground facility owned by the French Marine, the “Souterrain du
97 Roule”, at Cherbourg (Figure 1). A drift does actually exist on both tiltmeters directions (EW
98 and NS). However, it only causes interferences within the long period variations for more
99 than one week, which can be eliminated by standard filtering methods to focus on the diurnal
100 tidal band and its harmonics without spectral windowing artefacts.

101 2.2. Site effects

102 Site effects include topographic, cavity and geological effects. It is not only a magnification
103 or reduction, new tilt signals can be added by strain-tilt coupling, typically resulting in a
104 phase shift. The first who provided a useful approach to deal with such undesirable effects
105 was Harrison (1976). An essential characteristic of site effects is the relative phase shift with
106 respect to its theoretical value, which can reach as much as 40° (Lecolazet and Wittlinger,
107 1974).

108 In the paper by King *et al.* (1976) two issues dealing with the correction of site effects are
109 mentioned: first the practical problem of constructing and checking large three-dimensional
110 models, and second the difficulties of obtaining the correct input data for the models.

111 Nowadays, the Finite Element Method (FEM) could be applied (see for instance Kroner *et al.*
112 2005). These authors also remind the work of Itsuei *et al.* (1975) in which the problem of
113 fractures or other inhomogeneities in the vicinity of the observation site, that cannot be
114 adequately mapped (as in our case), are introduced. They proposed a method for removing the
115 site effects without need for modelling by using a response method actually based on the
116 seismic response of the Rayleigh waves. Neither of these methods can be used here. As stated
117 by King *et al.* (1976) the first method is valid only for sites distant from ocean loading and the
118 second requires at least the vertical component of the Rayleigh wave which is not available in
119 our case.

120 However two points must be emphasized that show that site effects can be supposed to be
121 small. Firstly, the crust flexure results mainly from remote surface loads and only involves
122 Newtonian body forces as a minor contribution. The direct Newtonian attraction itself is tiny
123 as it results from an elementary calculation. Indeed, the vertical deviation which is the main
124 effect of the near oceanic attraction can be neglected, and then the associated cavity effect too.
125 Secondly, tiltmeters have been installed more or less in the middle of the tunnel (a symmetry
126 axis), where the disturbing effect is supposed to vanish.

127 The solution we finally adopted is neglecting potential site effect corrections, assuming it is
128 less critical than in the frame of a body Earth Tide study. Finally, remembering that Lecolazet
129 and Wittlinger (1974) attributed a significant phase shift to the cavity effect, we state that the
130 undetectable phase difference between the observed and the modeled tidal tilt variations will
131 be an *a posteriori* justification of the reduced rule of site effect.

132 **2.3. Atmospheric contribution on tilt.**

133 The atmosphere contributes to the tilt as any other moving mass (Boy *et al.*, this issue). Two
134 deformation processes have to be modeled: direct attraction (modifying the equipotential),

135 and the elastic deformation due to the additional pressure on the crust, which also implies
136 mass redistribution and thus an effect on the geoid (Farrell, 1972). The formalism to compute
137 the atmospheric contribution is similar to that used in the oceanic or continental
138 (hydrological) loading problems, except that one should consider here that the station is inside
139 the atmosphere shell. As in the hydrological case, tilts are only influenced by the lateral
140 pressure gradient (Rerolle et al., 2006). It implies that the classical admittance method cannot
141 be applied in our case. Hence, two methods can be used to correct the atmospheric pressure
142 contribution. First one could involve a local barometer network, which requires an extensive
143 installation because of the different spatial scales involved in the deformation. Four
144 barometers have been set up around the tilt site, 1 km from it. Unfortunately, this data did not
145 attempt to provide accurate pressure effect prediction to correct the tilt time series. Some
146 other experiences made recently in the Vosges Mountain, enforced by modeling
147 computations, show that it would be necessary to have at our disposal both a tight network of
148 barometer immediately around the tiltmeter and more remote ones to take into account
149 atmospheric effects at several spatial scales (Longuevergne, 2008). An alternative method
150 makes use of atmospheric data as provided by meteorological models. However, the sampling
151 rate of these models is usually 6 hours, and does not allow to study phenomena below 12
152 hours. From a spectral point of view, pressure effects superimpose a noisy noise on periodic
153 signals. If a good atmospheric pressure correction is expected to improve the S/N ratio, we
154 suspect that it would be only a light improvement in our spectral analysis because the
155 atmospheric energy is not concentrated on tidal peaks in the frequency domain. Precisely, let us
156 consider the signal level close to M2. Figure 3 shows that it reaches about $0.003 \mu\text{rad}$. Hence
157 the pressure effect cannot exceed this level, which is about 1/100 of the amplitude of M2. Then
158 M2 is affected by less than 1% by the pressure effect. This is less than the calibration error,
159 and then dropping the pressure effect will not cause serious misinterpretation. Similar
160 reasonings apply for the other harmonics. In addition, it is worth noticing that the pressure

161 effect on that coastal border is complicated by the dynamic response of the ocean , referred as
162 the “Inverted barometer hypothesis” (see Carrère and Lyard, 2003; Boy *et al.*, this issue).
163 Finally, we dropped this correction which is practically difficult to perform, but in the same
164 time probably not critical for our purpose, especially because the expected improvement will
165 be obsolete when considering the poor calibration factor accuracy.

166 Traditional Earth Tide (ET) studies have benefited from gravity observations, such as the
167 GGP experiment (<http://www.eas.slu.edu/GGP/ggphome.html>). Most of the geodesists
168 consider that the discrepancies between tidal observations and corresponding models are very
169 tiny. Actually, they are much smaller toward the inner continental stations where the
170 influence of oceanic loadings is reduced. The agreement between the Love numbers used to
171 compute visco-elastic Earth tides and those derived from GGP GGP (see Baker and Bos,
172 2003; Boy *et al.*, 2003) cryogenic gravimeter data is better than 1/100. This is indeed
173 negligible when considering the tiltmeter factor calibration accuracy and one can assume that
174 the modelled Earth tide elastic contribution is very accurate and can be subtracted from the
175 raw data to keep only oceanic loading effects. Since cavity and site effect are assumed to be
176 small, we consider that it is neither necessary to correct the Earth tide contribution for it to
177 perform this subtraction. Finally, we consider that the error associated with site effects is
178 reduced due to (1) the position of the tiltmeters in the center of the tunnel and (2) the reduced
179 amplitude of the Earth Tide by a factor 5 with respect to loading and (3) the feature of the tilt
180 which involves limited body forces.

181 **3. Signal processing and spectral analysis.**

182 The whole time-series are available on request to the main author.

183 **3.1 Basic spectral analysis**

184 Tilts were initially sampled at 30 sec intervals. We applied high-pass filtering (to remove the
185 drift) and resampling with low-pass filtering to avoid aliasing. This finally restricts the
186 effective bandwidth to periods between 10 minutes and 72 hours. Raw and filtered signals are
187 plotted in Figure 2. The amplitude spectra of the filtered signals are plotted on Figure 3. We
188 chose a spectral normalization which preserves the amplitude of the periodic signal rather
189 than the spectral power density. Hence, the tidal wave amplitudes can be directly read in
190 microradians.

191 The spectra show several harmonics of the diurnal tidal waves. They are directly linked to the
192 non-linear hydrodynamical waves in the English Channel and do not result from any kind of
193 non-linearity of the Earth elastic response. Modelling the observed amplitudes requires the
194 computation of these non linear waves by using the most complete oceanic charts, involving
195 hydrodynamic modelling plus data assimilation, and to combine them with the rheological
196 response of the Earth. However, the difficulties to retrieve upper order waves lie in the
197 limitation in the mesh and restitution sharpness as seen by altimetric satellites; more exactly
198 it depends on the trade-off between time and space sampling, both limited in practice
199 (Cartwright and Ray, 1990). This becomes more difficult as the order increases, since the
200 higher the order, the smaller the typical wavelength to be taken into account.

201 Several points should be highlighted here:

- 202 - the amplitudes of even orders are greater than for other harmonics. This is expected
203 since they are successive harmonics of the M2 dominant group.
- 204 - Tiltmeters are able to record nonlinear waves up to 10 cycles/day. Note that neither
205 loading gravity studies (Boy *et al.*, 2004) nor any other integrative geodetic method
206 have been able to “see” these higher harmonic signals (although they are clearly seen
207 in tide gauge records, of course). Hence tiltmeters are confirmed to be very sensitive

208 tools to observe the deformation induced by oceanic tides at the regional scale, and
209 can be used up to high harmonics to validate non linear oceanic models.

210

211 3.2. Tidal analysis

212 Earth tide analysis softwares are designed to estimate the transfer response of the Earth with
213 respect to the astronomical gravity potential, usually providing the delta and gamma factors
214 (Melchior, 1983). To search for higher tidal harmonics in the tiltmeter records, we therefore
215 looked for tidal analysis tools which actually are standard within the sea-level community.
216 We used the MAS software developed by Simon (2007) which implements a general method
217 for analysing sea level heights. Pouvreau *et al.* (2006) compared MAS to the well-known and
218 widely distributed T_TIDE software (Pawlowicz *et al.* 2002), and could not notice any
219 significant difference from both sets of estimated tidal amplitudes at Brest. A drawback of the
220 current T_TIDE release is, however, that it cannot analyse datasets longer than one-year,
221 whereas MAS is successfully applied over periods even longer than a century.

222 Table 1 shows the main tidal constituents that we obtained from the ocean-like tidal harmonic
223 analysis performed on the tiltmeter observations that were previously corrected for the Earth
224 tides over the period 2004/03/09 to 2005/07/18. These analysis have been gathered here for
225 comparison with the models discussed in the next paragraph, but those only involve the major
226 eight constituents.

227

227 **4. FES2004/NEA time modelling and testing increasing contributive distance**

228 The modelling is performed by combining FES2004 global oceanic model (Lyard *et al.*
229 2006), and the refined NEA (North East Atlantic tidal solution) model in the close Atlantic
230 and English Channel (Pairaud *et al.*, 2008). To perform the computation, the jointed model
231 heights are convolved in two dimensions by using the radial tilt Green Function provided in
232 Pagiatakis (1990).

233 We have plotted on Figure 4 the modelled oceanic loading and the Earth Tide contribution, as
234 well as the sum of these two signals and compared them with the observation. The chosen
235 window permits to illustrate the best and the worst agreements. The largest discrepancies
236 between modelled and observed oceanic loading occur for large tidal ranges. At the end of the
237 window, during small tidal ranges, the agreement is far better. In general, the EW component
238 is better modelled than the NS component. This may be linked to the orientation of the coast
239 (EW) which is located 2 km northwards of the observing site.

240 We do not know the origin of these discrepancies and their variations in time. However, we
241 form the hypothesis that it could come from the interference arrangement between the main
242 tidal M2 group and the overtones (nonlinear harmonics). We only took into account 8 waves
243 in the diurnal and semi-diurnal bands here and none of the non-linear tides.

244 **Sensitivity of the tilts to the remoteness of the loads.**

245 To study the tilt as a function of the distance to the loads, we chose an adapted geographical
246 windowing, as shown in Boy *et al.* (2003) to represent the different contribution of individual
247 areas.

248 The computation was performed by distinguishing three exclusive zones: this enabled to study
249 the influence of nearby, medium range and remote oceanic loading effects. Zone 1 (Z1): from
250 -5° to 1.5° in longitude and 48.5° to 51.25° in latitude, based on NEA2004 model (Pairaud *et*

251 *al.*, 2008) corresponds to the English Channel; Zone 2 (Z2): from -20° to 14° in longitude and
252 30° to 61° in latitude, also based on NEA2004 model, is a medium range zone excluding Z1.
253 Zone 3 (Z3), based on FES2004 (Lyard *et al.*, 2006), is global and covers the other parts of
254 the world excluding Z1 and Z2.

255 Figure 5 shows the M2 wave amplitude and the three zone boundaries. Figure 6 highlights the
256 cumulative contributions of each of these 3 zones for all the diurnal and semi-diurnal waves.
257 It clearly showed the effect of the local magnification in the semi-diurnal band (N2, M2, S2,
258 and K2). Large zooms were required to see further contributions; the local contribution was
259 definitely dominant, and one could neglect the farther load contributions in the model without
260 significant loss.

261 The diurnal waves (O1, P1, K1, Q1) formed a second class of patterns. Though the local zone
262 (English Channel) dominated the signals, the Atlantic and remote zones were almost of the
263 same order of magnitude and none of the contributions could be neglected. This could be
264 explained by the fact that the diurnal waves were not as amplified by the Channel as the
265 semi-diurnal waves.

266

267 **5. Comparison between final model and observed data.**

268 The phasor diagram given in Figure 7 shows the residual discrepancy between the observed
269 data (from which the Earth Tide contribution was previously removed) and the models. Using
270 FES2004 alone provided results that were not in good agreement with the observations,
271 especially as far as the NS component is concerned. By substituting FES2004 with NEA2004
272 in the area close to the site, a real improvement is achieved, but a significant discrepancy
273 remains. Since the main improvement arising from FES2004 to NEA is the finer spatial
274 resolution of the grid used in the computation, one could conclude that the residual
275 discrepancy was mainly due to the coarseness of the grid still in use, which is a more critical
276 issue when dealing with tilt than when dealing with gravity or vertical displacement time-

277 variations. The successive points “FES2004”, “FES2004+NEA” are often quite on a line that
278 seems on the way to tend to the observation: see M2, S2, K2, K1. The improvement appeared
279 to be better on the NS component than on the EW one.

280 The less the amplitude of the wave, the less the relative accuracy of this line pattern; see for
281 instance the EW component of Q1. In such case, it is likely that the random noise still hide the
282 signal and/or prevent the model to be accurate.

283

284 **6. Discussion and Conclusions**

285 The sensitivity of the tiltmeters allows to observe the loading effect with a high signal/noise
286 ratio. This implies that assuming a known mechanical response of the Earth, tiltmeters can be
287 used to validate oceanographic models and nonlinear tides. Contrary to tide gauges whose
288 spatial sensitivity is strictly local (and can be affected by the harbour inner architecture), the
289 tilt offers an integrative measurement of the behaviour of the ocean with a regional spatial
290 sensitivity. This is the case for the M2 group; the wave amplitude is quickly decreasing when
291 the distance to the coast increases, making the remote contribution really negligible. The main
292 remaining issues are: 1) the site effect, which is difficult to estimate in most cases, 2) the lack
293 of atmospheric detailed data to correct for pressure within this short period band, and 3) the
294 necessity to take into account a dynamical and coupled atmosphere-ocean modelling (see Boy
295 *et al.*, this issue), 4) the difficulty to achieve a good accuracy in the calibration factor for this
296 kind of tiltmeters. Further improvement of the computing grid sharpness will certainly
297 improve the fit and all these challenges could be tackled in the future. Currently new
298 experiments are carried on in Brittany near Ploemeur in France (Bour *et al.*, 2008) which
299 could serve to improve our knowledge. Indeed, long-base hydrostatic tiltmeters have been set
300 up in shallow galleries. They have been recording for a few months. Both calibration
301 uncertainties and site effects will be easier to solve there for that kind of instruments. In

302 parallel, atmospheric sampling rates and coupled modelling with the oceans are continuously
303 improving.

304 Due to its features and assuming further improvements, tilt could become a systematic tool to
305 test oceanic models as far as non linear high harmonics are concerned. Neither gravity nor
306 GPS techniques are able to see M4, M6, M8 and M10 waves with such a signal/noise ratio as
307 the one reached by tiltmeters today.

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309

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320

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324 **References**

- 325 Baker, T.F. and M. S. Bos, 2003. Validating Earth and ocean tide models using tidal gravity
326 measurements. *Geophys. J. Int.*, 152, 468-485.
- 327 Beavan, R.J., 1974. Some Calculations of Ocean Loading Strain Tides in Great Britain,
328 *Geophys. J. R. Astr. Soc.*, Vol . 38, 1, pp. 63-82.
- 329 Blum, P., 1962. Contribution à l'étude des variations de la verticale en un lieu, *Ann.*
330 *Geophys.*, 19, 215-243.
- 331 Bour, O., Caudal, J.P., Le Borgne, T., Moreau, F., Labasque, T., Boudin, F., Aquilina, L.,
332 Ruelleu, S., Dauteuil, O., Jacob, T., Durand, S., Maia, M., Biessy, G., Tarits, C., Bayer, R., Le
333 Moigne, N., Morel, L., Henin, O., Ferrand, A., Davy, P., 2008. The Ploemeur research site :
334 goals and motivations for long-term monitoring and groundwater experiments, AGU Fall
335 Meeting, San Francisco, USA, 15-19 December 2008.
- 336 Boy, J.P., Llubes, M., Hinderer, J., and Florsch, N., 2003. A comparison of tidal ocean
337 loading models using superconducting gravimeter data. *J. Geophys. Res.*, 108, B4, 2193, doi:
338 10.1029/ 2002JB002050, 2003.
- 339
- 340 Boy, J.-P., M. Llubes, R. Ray, J. Hinderer, N. Florsch, S. Rosat, F. Lyard and T. Letellier,
341 2004, Non-linear oceanic tides observed by superconducting gravimeters in Europe, *J.*
342 *Geodyn.*, 38, 391-405.
- 343
- 344 Boy, J.-P., L. Longuevergne, F. Boudin, T. Jacob, F. Lyard, M. Llubes, N. Florsch and M.-F.
345 Esnault, 2009. Modelling atmospheric and induced non-tidal oceanic loading contributions to
346 surface gravity and tilt measurements, *J. Geodyn.*, this issue.
- 347

- 348 Braitenberg, C., and Zadro, M., 1999. The Grotta Gigante horizontal pendulums -
349 instrumentation and observations. *Bollettino di Geofisica Teorica ed Applicata*, 40, no 3-4,
350 pp. 577-582.
- 351
- 352 Carrère, C. and F. Lyard, 2003. Modeling the barotropic response of the global ocean to
353 atmospheric wind and pressure forcing - Comparisons with observations, *Geophys. Res. Lett.*,
354 30 (6), 1275, doi:10.1029/2002GL016473.
- 355 Cartwright, D.E., and Ray, R.D., 1990. Oceanic tides from Geosat altimetry. *J. Geophys.*
356 *Res.*, 95 (C3), pp. 3069–3090.
- 357 Farrell, W., 1972. Deformation of the Earth by surface load, *Review of Geophysics Space*
358 *Physics*, 10(3), 761–797.
- 359
- 360 Harrison, J. C., 1976. Cavity and topographic effects in tilt and strain measurements. *J.*
361 *Geophys. Res.*, 81, 319 – 328
- 362
- 363 Itsuei, U.J., Bilham, R.G., Gouly, N.R., and King, G.C.P., 1975. Tidal strain enhancement
364 observed across a tunnel, *Geophys. J. R. astr.Soc.*, **42**, 555
- 365
- 366 King, G., Zürn, W., Evans, R., Emter, D., 1976. Site Correction for Long Period
367 Seismometers, Tiltmeters and Strainmeters. *Geophysical Journal International*, vol. 44, issue
368 2, pp. 405-411.
- 369 Kroner, C., Jahr, T., Kuhlmann, S., & Fisher, K., 2005. Pressure-induced noise on horizontal
370 seismometer strainmeter records evaluated by finite element modelling, *Geophys. J. Int.*, 161,
371 167–178.

372 Lecolazet, R. & Wittlinger, G., 1974. Sur l'influence perturbatrice de la deformation des
373 cavités d'observation sur les marées clinométriques, C. R. Acad. Sc. Paris, 278, 663–666.

374

375 Llubes, M., and Mazzega, P., 1997. Testing recent global ocean tide models with loading
376 gravimetric data, Progress In Oceanography, 40, 1-4, pp. 369-383, [doi:10.1016/S0079-](https://doi.org/10.1016/S0079-6611(98)00014-7)
377 [6611\(98\)00014-7](https://doi.org/10.1016/S0079-6611(98)00014-7)

378

379 Llubes, M., Florsch, N., , Amalvict, , M., Hinderer, J., Lalancette, M.F., Orseau, D., et Simon,
380 B., 2001. Observation gravimétrique des surcharges océaniques : premières expériences en
381 Bretagne. C.R. Acad. Sci, Earth and Planetary Sciences 332, 77-82.

382

383 Llubes, M., Florsch, N., Boy, J.P., Amalvict, M., Bonnefond, P., Bouin, M.N., Durand, S.,
384 Esnault, M.F., Exertier, P., Hinderer, J., Lalancette, M.F., Masson, F., Morel, L., Nicolas, J.,
385 Vergnolles, M., Wöppelmann, G., 2008. Multi-technique monitoring of ocean tide loading in
386 Northern France. C. R. Geoscience 340, 379–389

387

388 Longuevergne, L. (2008), Contribution a l'Hydrogéodésie, Ph.D. thesis, 300 pp, Université
389 Pierre et Marie Curie. Can be downloaded at :

390 http://tel.archives-ouvertes.fr/index.php?halsid=0t01nopdml7t5508qotbnu7v1&view_this_doc=tel-00319205&version=1

391

392 Lyard, F., Lefevre, F., Letellier, T., and Francis, O., 2006. Modelling the global ocean tides:
393 modern insights from FES2004. Ocean Dynamics, 56, 5-6, 394-415. DOI 10.1007/s10236-
394 006-0086-x.

395 Melchior, P., 1983. The Tides of the Planet Earth, Pergamon Press.

- 396 Pagiatakis, S., 1990. The response of a realistic Earth to ocean tide loading, *Geophys. J. Int.*,
397 103, 541–560. DOI: 10.1111/j.1365-246X.1990.tb01790.x
- 398 Pawlowicz, R., Beardsley, B., and Lentz, S., 2002. Classical tidal harmonic analysis error
399 estimates in MATLAB using T_TIDE. *Comput. Geosci.* 28, 929–937.
- 400 Pairaud, I.L., Lyard, F., Auclair, F., Letellier, T., Marsaleix, P., 2008. Dynamics of the semi-
401 diurnal and quarter-diurnal internal tides in the Bay of Biscay. Part 1: Barotropic tides.
402 *Continental Shelf Research* 28 (2008) 1294– 1315.
- 403 Pouvreau, N., Martin Miguez, B., Simon, B, and Woppelmann, G., 2006. Evolution of the
404 tidal semi-diurnal constituent M2 at Brest from 1846 to 2005. *C. R. Geoscience*, 338, pp.
405 802–808.
- 406 Rerolle, T. , Florsch, N., Llubes, M., Boudin, F., and Longuevergue, L., *Inclinometry, a new*
407 *tool for the monitoring of aquifers? C. R. Geoscience* 338 (2006).
408 doi:10.1016/j.crte.2006.07.004
- 409
- 410 Saleh, B., Blum, P.A., and Delorme, H., 1991. New silica compact tiltmeter for deformations
411 measurements, *J. Survey Eng.* 117 , pp. 27–35.
- 412 Simon, B, 2007. *La marée océanique côtière. Collection “Synthèses”*, Ed. Institut
413 Océanographique, 433 pp.
- 414
- 415 Vey,S. , Calais, E., , Llubes, M., Florsch, N., Woppelmann, G., Hinderer, J., Amalvict, M.,
416 Lalancette, M.F., Simon, B., Duquenn F., Haase, F.S., 2002 GPS measurements of ocean
417 loading and its impact on zenith tropospheric delay estimates: a case study in Brittany,

418 France. Journal of Geodesy, vol. 76, 8, pp 419-427.

419

420 Wilcok, W.S.D, 2001. Tidal triggering of microearthquakes on the Juan de Fuca Ridge. GRL,

421 Vol. 28, N° 20, pp. 3999-4002,.

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426

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426 **Table captions**

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428 Table 1 shows 1) the main tidal constituents obtained from the ocean-like tidal harmonic
429 analysis performed on the tiltmeter observations that were previously corrected for the Earth
430 tides over the period 2004/03/09 to 2005/07/18; 2) the prediction of amplitude and phase for 8
431 waves based on FES2004 and NEA2004 model

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441 **Figure captions:**

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Figure1 : Site location and installation of a Blum Pendulum in the “Souterrain du Roule” at

444 Cherbourg (France)

445

446 Figure2 : EW and NS raw and band-pass filtered tilt records at Cherbourg

447

Figure 3 : Fourier analysis (periodograms) of the tilt records reveal a high signal/noise ratio
449 of 100 (40 dB) at 2 cycle/day. Peaks are visible even at 10 cycles/day.

450 .

Figure 4: on the bottom part, Earth tide and loading models are shown separately, while there
are summed in the top part of the figure. In both cases, the observation is also plotted and
shows a greater amplitude than the model. The misfit could be due to non-linear tides that are
454 not included in this computation.

455

Figure5 : M2 amplitude from FES2004 model (top), and NEA-2004 (bottom). The
NEAmodel is computed by using an unstructured grid called T-UGAm (Courtesy I.L. Pairaud
et al., 2008). The figure also shows the three zones used to perform the computation with
increasing involved radius and surface, Zones 1, 2 and 3 as described in the text.

Figure 6: phasor diagram of the cumulative contribution of the 3 different zones for all diurnal
461 and semi-diurnal waves.

Figure 7: phasor diagram showing the observation and how the model FES2004 and FES2004
463 improved with NEA tend to fit the data.

Table 1

Component		NS						EW					
Tidal constituent		Observation		FES+NEA 2004		FES 2004		Observation		FES+NEA 2004		FES2004	
Name	Doodson	Amp (nrad)	Phase (°)	Amp (nrad)	Phase (°)	Amp (nrad)	Phase (°)	Amp (nrad)	Phase (°)	Amp (nrad)	Phase (°)	Amp (nrad)	Phase (°)
M2	BZZZZZ	394.22	250.9	265.19	257.1	196.79	264.7	437.19	326.3	367.37	333.7	335.06	334.8
S2	BBXZZZ	137.88	291.0	89.33	298.0	69.04	300.1	149.13	8.3	128.5	21.5	111.11	4.5
N2	BYAZZZ	82.45	232.5	45.76	236.0	40.00	264.7	86.92	308.9	70.48	317.4	63.26	315.6
K2	BBZZZZ	40.14	287.9	23.40	293.3	16.01	299.8	40.31	1.1	28.51	27.2	28.63	19.8
K1	AAZZZZA	25.25	147.2	13.87	136.6	9.85	136.3	33.25	275.5	9.45	279.1	8.02	275.5
O1	AYZZZZY	5.00	63.8	9.78	28.1	6.05	26.9	18.03	242.6	7.99	160.1	7.23	159.4
P1	AAXZZZY	9.21	127.9	5.14	135.6	3.26	300.1	12.17	294.2	3.17	276.5	2.82	274.7
Q1	AXZAZZY	4.51	300.8	2.83	344.8	3.24	360.0	2.21	267.9	2.85	112.9	2.46	112.5
M4	DZZZZZ	3.04	8.4					1.22	84.6				
MS4	DBXZZZ	1.88	68.0					0.84	138.6				
MN4	DYZAZZZ	1.03	344.6					0.46	68.5				
M6	FZZZZZ	0.65	90.4					0.37	268.8				
2MS6	FBXZZZ	0.77	137.9					0.31	317.1				
2MN6	FYZAZZZ	0.46	65.4					0.17	230.5				
5MS8	HXBZZZ	0.76	60.9					0.15	5.7				