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# Tide gauge datum continuity at Brest since 1711: France's longest sea-level record

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[1] The issue of a possible tide gauge datum discontinuity at Brest, caused by the bombing of the city in August 1944, is discussed. This issue is very important, as many scientists have used this long record to derive a long-term sea level trend estimate for use within global sea level rise studies. A detailed analysis of historical leveling information, and comparison of sea level data between adjacent stations, proved to be worthwhile, even beyond this initial scope of the study: it led to an accurate datum connection between recently rediscovered 18th century sea level data (back to 1711) and those of the present day. The study provides additional evidence that the onset of recent rapid sea level rise most likely took place in the late 19th century, in agreement with the nearby Liverpool sea-level record and with independent results from sediment cores collected in salt marshes located in both hemispheres. **Citation:** Wöppelmann, G., N. Pouvreau, A. Coulomb, B. Simon, and P. L. Woodworth (2008), Tide gauge datum continuity at Brest since 1711: France's longest sea-level record, *Geophys. Res. Lett.*, 35, L22605, doi:10.1029/2008GL035783.

## 1. Introduction

[2] The Brest sea level record, dating back to 1807, is the longest mean sea level record in the data archive of the Permanent Service for Mean Sea Level (PSMSL) [Woodworth and Player, 2003] and the Brest station nowadays contributes to the Global Sea Level Observing System [Intergovernmental Oceanographic Commission (IOC), 1997]. Brest data have been included in many sea level studies including those concerned with recent sea level rise [e.g., Cartwright, 1972; Gornitz *et al.*, 1982; Barnett, 1984; Pirazzoli, 1986; Woodworth, 1987, 1990, 1999; Trupin and Wahr, 1990; Douglas, 1991, 2001; Araujo *et al.*, 2002; Holgate and Woodworth, 2004; Nakada and Inoue, 2005; Church and White, 2006; Bindoff *et al.*, 2007; Leorri *et al.*, 2008]. Its time series is substantially complete but small gaps can be filled by interpolation, leading to a data set which is 92% complete between 1807 and the present day [Pouvreau *et al.*, 2006; Wöppelmann *et al.*, 2006]. A few multi-year gaps exist in the 1830s, 1850s and 1940s. The early gaps probably correspond to data that were lost, and may one day be

rediscovered, whereas the later gap was due to a recording interruption. The question of the datum continuity of the Brest tide gauge record in this period has been raised: comparing both Brest and Newlyn mean sea-level records, Douglas [2001, 2008] pointed to an apparent offset of about 20 mm in 1944, suggesting in his paper of 2001 that datum continuity may have been lost after the destruction of the Brest tide gauge during the bombing of the city in August of that year. A 20 mm offset in 1944 would lead to a bias of 0.3 mm/year in the 20th century trend estimate for Brest (using the formula given by Van Onselen [2000, p. 187]). Such a bias may explain why the rates of relative sea level rise at Brest and Newlyn in the 20th century are different (1.3 mm/year and 1.7 mm/year respectively) [e.g., Douglas, 2001]. Woodworth [1987] previously noted this difference, which is difficult to explain when considering that Brest and Newlyn sites are relatively close (~210 km), and there is no geological evidence for a difference of the order of 0.4 mm/year in vertical land movement [Emery and Aubrey, 1991]. The datum continuity at Brest is thus an important issue within studies of sea level trends. Section 2 presents the two types of data used to address this issue, while section 3 examines the available historical leveling information, and section 4 extends the station comparisons carried out by Douglas [2008] to other neighboring stations. Section 5 discusses the results obtained.

## 2. Data Sets

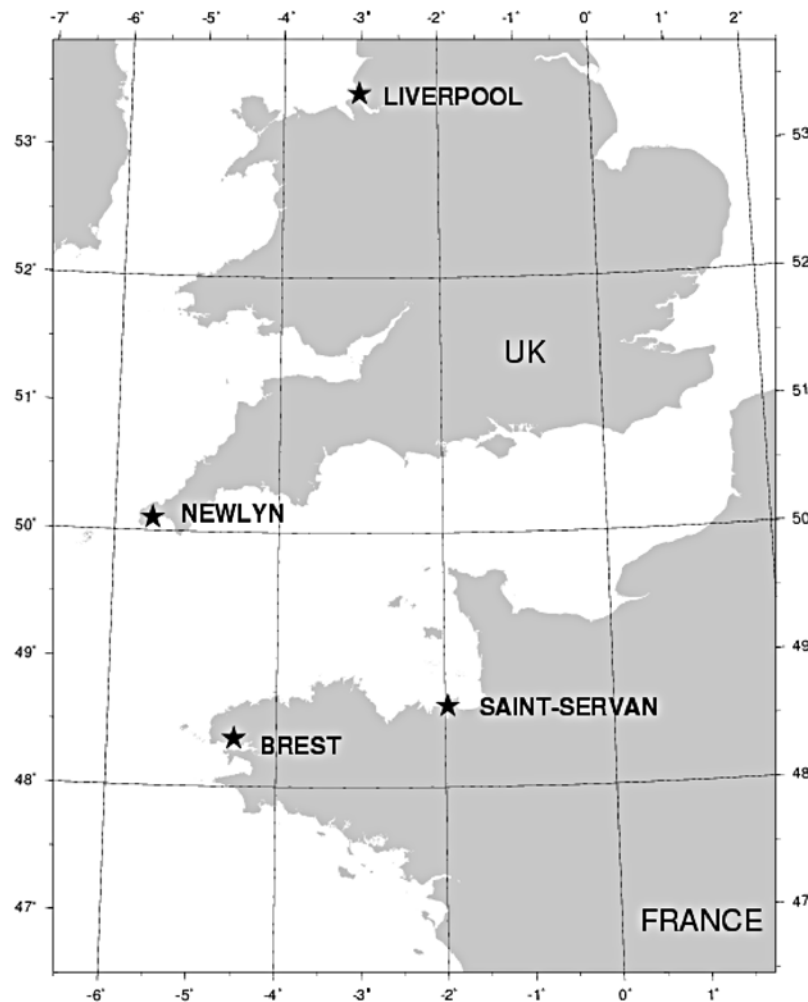
[3] Two types of data have been used to assess the continuity of the Brest tide gauge datum: (1) data obtained from historical leveling surveys involving the primary tide gauge benchmark, usually designated as the 'TGBM', and (2) tide gauge records from neighboring stations. The TGBM is a key element of a tide gauge station since it defines the datum to which the values of sea level are referred [e.g., IOC, 1985; Wöppelmann and Pirazzoli, 2005]. It serves to construct long-term sea level time series, even if parts of the time series were obtained from different gauges and different benchmarks (as long as these benchmarks were connected to the TGBM by high-precision leveling). The TGBM is ultimately the source of the long-term coherence and stability of the measurements. Therefore, it is recommended practice [IOC, 1985] to preserve the datum by installing and connecting by high-precision leveling a set of five to ten benchmarks within a few hundred meters of the tide gauge. Fortunately, this has been the case at Brest. Two tide gauge benchmarks survived the bombing of Brest during the Second World War, among them the TGBM, which was originally chosen as the 'most stable' mark.

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**Figure 1.** Neighboring stations with long sea-level records: Newlyn (about 210 km from Brest), Saint-Servan (about 190 km) and Liverpool (about 570 km).

[4] The French hydrographic service (SHOM), which operates the tide gauge, has maintained a reasonably well documented history of the tide gauge maintenance. In addition, we have searched the archives of the French mapping agency (IGN) for documented historical levelings in the vicinity of the Brest tide gauge so as to provide a link between the tide gauge and the local network of stable benchmarks. Records of at least six first-order leveling surveys were found at IGN encompassing the period of interest: 1889, 1938, 1962, 1973, 1985 and 1996. These data are examined closely in the next section.

[5] Annual mean sea level values from Brest and Newlyn were obtained from the PSMSL ‘Revised Local Reference’ (RLR) data set. There are no other suitable RLR records from neighboring stations. However, to further extend the comparison, we made use of the adjusted Mean High Water (MHW) time series for Liverpool [Woodworth, 1999], also available from the PSMSL databank. This time series starts in 1768 and can be used in conjunction with the Brest annual MHW time series obtained by Wöppelmann *et al.* [2006], a data set that spans c.300 years since 1711. In addition, though discontinuous and not yet published officially, the historical tide gauge record of Saint-Servan

(France) was also included in this study. It is located 190 km from Brest, a comparable distance to that of Newlyn (Figure 1). These measurements were obtained at the same location and with respect to the same hydrographic datum since 1850, according to the documentation found in the SHOM archives. Chazallon [1859] expressed concerns about the quality of early data from 1850 to 1856 and they have not been included. Saint-Servan data from 1941 to 1944 were also omitted because of the lack of detailed information on the German tide gauge used during this period. Figure 1 shows the locations of the tide gauge sites used in this study.

### 3. Datum Continuity From Leveling Surveys

[6] Six first-order leveling surveys were found in the IGN archives, each including some of the Brest tide gauge benchmarks and encompassing the Second World War. Circumstances did not require a redefinition of the TGBM from amongst the set of local benchmarks over the whole period covered by the six surveys (1889 to 1996; see Table 1). Two benchmarks existed for the whole period, including the years around 1944, and fortunately one of

**Table 1.** Leveling Results at Different Epochs for the Brest Primary Tide Gauge Benchmark NO-1 (1889 Marker Name) With Respect to Neighboring Benchmarks of the 1st Order Leveling Network

Marker (1889) <sup>a</sup>	1889 Height Differences <sup>b</sup>	Marker (1938) <sup>a</sup>	1938 Height Differences <sup>b</sup>	Marker (1962) <sup>a</sup>	1962 Height Differences <sup>b</sup>	Marker (1973) <sup>a</sup>	1973 Height Differences <sup>b</sup>	Marker (1985) <sup>a</sup>	1985 Height Differences <sup>b</sup>	Marker (1996) <sup>a</sup>	1996 Height Differences <sup>b</sup>
								NO-30 (300)	+18.0338 m	→ NO-57	+18.0332 m
								NO-29 (1480 m)	-26.2236 m	→ NO-56	-26.2239 m
NO-1 (120 m)	+0.0808 m	NO-1	+0.081 m	NO-1	+0.0804 m	NO-1 (140 m)	+0.0823 m	→ NO-24	Not measured	→ NO-47	+0.0791 m
NO-2 (4130 m)	+16.5788 m	NO-2	+16.581 m	NO-2	+16.5876 m	NO-2		→ NO-23		→ NO-46	
NO-4 (500 m)	-2.2580 m	NO-4	-2.259 m	→ NO-8	-2.2590 m						
NO-5		NO-5		→ NO-9							

<sup>a</sup>The name of each benchmark (arrows outline a change in the marker name). The distances between two consecutive benchmarks are indicated in parentheses (distances refer to the path lengths of the leveling exercises and not the direct separation between marks).

<sup>b</sup>The observed leveling differences between two consecutive benchmarks.

them was the TGBM. Its designation changed several times from its original marker name NO-1, to NO-24 in 1985, and NO-47 in 1996.

[7] Since national height systems tend to be redefined occasionally, the important data to be examined here are the relative elevations which were measured between adjacent markers, not the heights themselves which rely upon the height system definition (origin and type of heights), as well as upon the numerical network readjustments. Table 1 summarizes the relevant leveling information. The relative elevations of both benchmarks NO-1 and NO-2 (using the 1889 mark names) to adjacent “stable” leveling markers were found to be the same within the estimated errors. First-order leveling is accurate to 1–2 mm over distances of a few kilometers [e.g., *Lallemant and Prévot*, 1927; *Bonnetain*, 1987]. Documentation of historical leveling between marks near to the gauge and marks at greater distance is more difficult to extract from the archives. We, however, succeeded to find a 1st order leveling path up to 20 km eastwards of Brest which was surveyed in 1889, 1962 and 1996, showing no anomalous elevation changes between the markers. Over longer distances (tens to hundreds of kilometers), leveling has been found to contain significant systematic errors that can cause spurious changes in the height of the benchmarks [e.g., *Ashkenazi et al.*, 1994; *Kasser*, 1989]. From the geodetic point of view, the entire Brest region, and in particular the area of land around the Brest tide gauge, is “stable” over the 1889 to 1996 period, and the Brest tide gauge datum can be considered as continuous at the millimeter level.

#### 4. Comparison to Adjacent Stations

[8] Figure 2a displays both the Brest and nearby Newlyn mean sea-level records. A 5-year average filter was applied in a similar way to *Douglas* [2008, Figure 13]. The Newlyn time series was shifted by a constant value such that Brest and Newlyn have the same average sea level after the data interruption in 1944. The curves in Figure 2a appear to describe a clear offset which was estimated to be  $19 \pm 2$  mm over the interval 1916–43. To confirm this result we attempted to detect the 20 mm offset using “buddy checking” with other neighboring stations [*IOC*, 1994; *Woodworth*, 2003]. As mentioned in section 2, there are no suitable nearby stations with good quality, long RLR

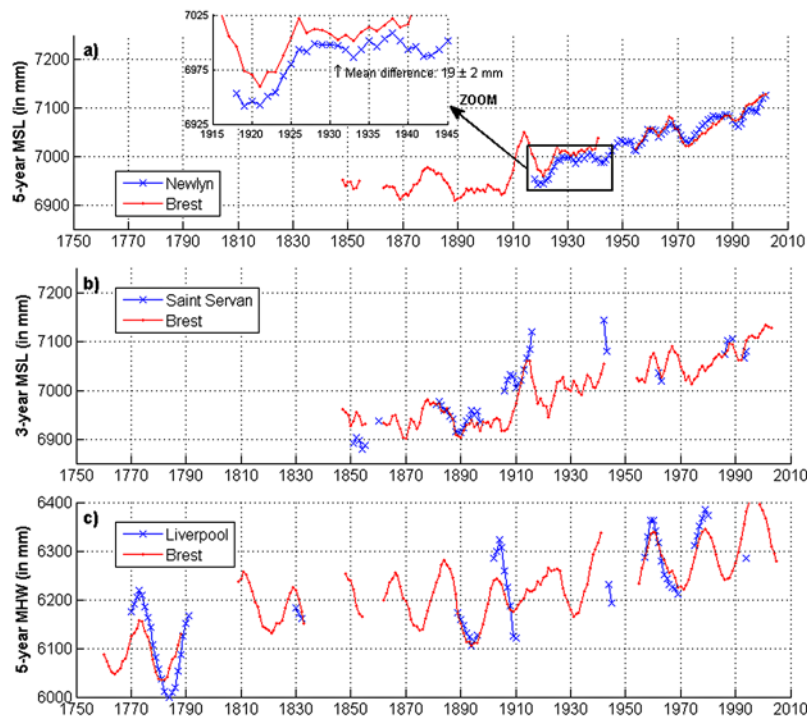
records. Buddy checking assumes that differencing two mean sea level time series will remove common oceanographic signals, isolating errors for further analysis (datum offsets, data spikes, etc.). However, if the stations are too far apart, there will be oceanographic differences and no exact “common mode”. As a consequence, no conclusive results could thus be derived from the comparisons carried out with Cascais (Portugal), about 1150 km from Brest, North Shields (UK) at about 760 km, Sheerness (UK) at about 510 km, Cuxhaven (Germany) at about 1100 km; nor either with Lagos (Portugal), or even Marseille (France) and Genova (Italy), which are located either further, or clearly in other basins under other oceanic and atmospheric influences.

[9] Figures 2b and 2c show the results from the two remaining records available for comparison with Brest. The annual mean sea level time series of Saint-Servan was computed following PSMSL standards: (1) no monthly value was calculated where more than 15 days were missing; (2) no annual mean was calculated if there were less than 11 monthly mean values; (3) the monthly values were weighted according to the number of valid days to compute the annual means. The early values of Saint-Servan (1850–1856), as well as those from the German tide gauge (1941–1944), are displayed in Figure 2b for the sake of completeness (see section 2). Due to the limited data in the Saint-Servan time series, the running means were computed over only 3-years. Although results using the Saint-Servan time series must be interpreted with caution (incomplete data, still to be published officially, thorough search for errors pending), no clear offset within the levels of variability in each record can be detected that would confirm a datum discontinuity at Brest around 1944. This conclusion is confirmed, again subject to the levels of variability in each record, by the Liverpool MHW data discussed below (Figure 2c).

#### 5. Discussion and Conclusions

[10] Estimation of relative trends in sea-level from tide gauge time series can be significantly biased if offsets are present. The documented historical first-order leveling surveys performed in the vicinity of the Brest tide gauge indicate that its datum remained “stable” and consistent at a few millimeters level over the period 1889–1996, in





**Figure 2.** Running means from: (a) Brest and Newlyn MSL values; (b) Brest and Saint-Servan MSL values; and (c) Brest and Liverpool MHW values. The Newlyn, Saint-Servan and Liverpool time series were shifted by a constant value that was estimated to match the Brest time series after the data interruption in 1944.

spite of the bombing of the city during the Second World War, and subsequent interruption in the Brest time series. No evidence of an offset affecting the datum continuity at Brest sea-level record can be detected by comparison to adjacent stations other than Newlyn. It is certainly tempting to apply an offset of about 20 mm to the Brest pre- and post 1944 records in order to bring its rate over the past century in agreement with the rate of sea-level rise obtained at Newlyn [Douglas, 2008], but this is definitely not supported by the analysis of historical leveling data, nor by extending the comparison to other sites. Hence, the issue of the difference of the relative sea level rise rates observed at Brest and Newlyn remains open. Specific research needs to be undertaken to solve this issue, including in particular long term GPS and absolute gravity measurements of vertical land movement at both sites, as well as a detailed analysis of historical leveling information at all other sites in the area including Newlyn.

[11] An interesting by-product of the datum comparison exercise is the close matching of the Brest and Liverpool time series over more than 200 years (Figure 2c). This result provides additional indirect evidence that the time series reconstruction of Brest sea levels from 1711 to the present was successfully carried out by Wöppelmann *et al.* [2006]. An important point to note is that both MHW series contain large nodal tidal variations, with the variations at Liverpool being 50% larger than those at Brest. Nevertheless, there are some similarities in their rates of relative sea level rise. Linear regressions of segments of the MHW records are similar: a trend of  $1.22 \pm 0.25$  mm/year is obtained for the 20th century at Liverpool [Woodworth, 1999], whereas a trend of  $1.14 \pm 0.18$  mm/year is obtained at Brest for the same period [Pouvreau, 2008]. The trends are further

consistent over the 19th century period ( $0.39 \pm 0.17$  mm/year and  $0.42 \pm 0.18$  mm/year respectively), indicating a recent significant increase in the rate of sea level rise at both sites. Moreover, the question when this apparent rise commenced is an important issue for long term sea level change, as a key observational constraint on climate models [Woodworth, 2006]. Both instrumental records show a roughly coincident increase in the rate of relative sea-level rise around the end of the 19th century. Our conclusion as to the timing of this onset of rapid sea level rise is consistent with independent results stemming from sediment cores collected in salt marshes, either in the northern hemisphere: near New York, USA [Donnelly *et al.*, 2004], Nova Scotia, Canada [Gehrels *et al.*, 2005], near Bilbao, Spain [Leorri *et al.*, 2008], or in the southern hemisphere: near Pounawea, New Zealand [Gehrels *et al.*, 2008]. The similar timing for the onset of the recent sea level rise, which has been found at both hemispheres from different types of data, supports the global significance and intensity of the acceleration of the sea-level rise compared to pre-industrial rates.

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