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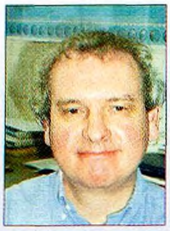

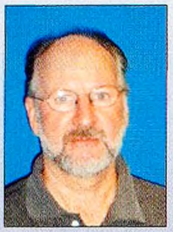

A One Year Comparison of Radar and Bubbler Tide Gauges at Liverpool

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Data from a new radar tide gauge and from a conventional bubbler pressure gauge were obtained over a period of a year at a test site at Liverpool in NW England. A comparison of the data sets has demonstrated that the two systems have similar individual accuracies of about 1 cm, consistent with the accuracies required for gauges in the UK and global networks. Radar technology has advantages over some other types of gauge with regard to ease of installation and maintenance. Therefore, our findings suggest that radar has to be given strong consideration in future applications, especially at locations where variations in water density preclude the effective use of pressure systems.

Introduction

Low cost radar tide gauges have become available during the last few years from several manufacturers. Although this technology is relatively new to most of the tide gauge community, as demonstrated by the mere brief mention of radar sensors in a recent review of tide gauge systems (IOC,

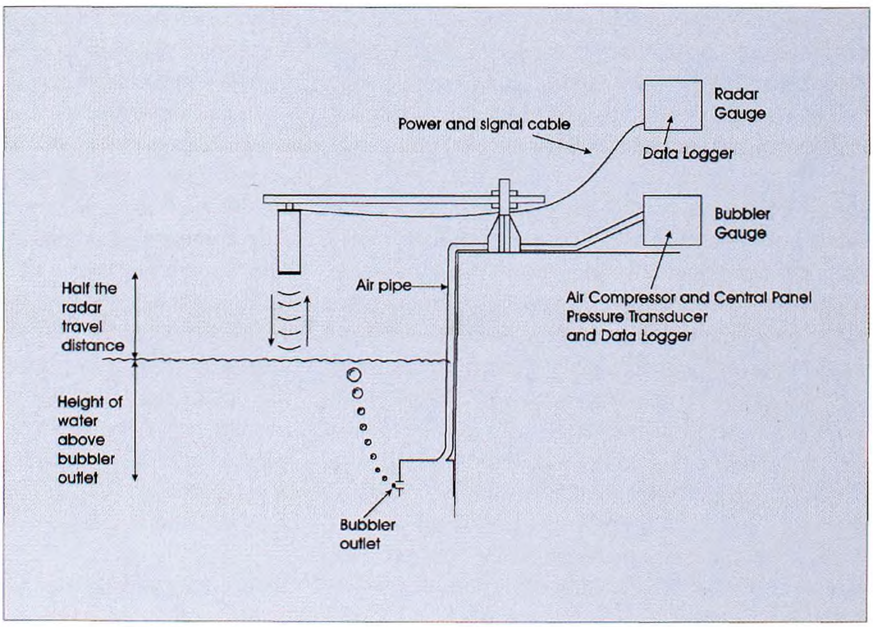

Figure 1: A schematic description of the radar and bubbler gauge systems at Liverpool

Figure 2: The OTT Kalesto gauge installed at Gladstone Dock, Liverpool

2002), their low cost means that they are now being purchased by a number of agencies as replacements for older instruments or as the basis for completely new networks. Therefore, it is essential that as much experience of them is shared as soon as possible.

Radar tide gauges are positioned several metres above the surface of the sea, or river or lake (Figure 1). Some radars measure changes in sea level by monitoring the time-of-flight of a radar pulse from a transmitter/receiver unit to the surface and back to the unit, while others use a Frequency Modulated Continuous Wave (FMCW) system in which transmitted radar waves are mixed with signals reflected from the surface to determine the phase shift between the two waves and thereby the range. They offer several advantages over float, pressure and acoustic gauges. The main advantage is the ease of installation and maintenance. Figure 2 illustrates that they require neither extensive fixings to a harbour wall or pier (as for a stilling well), nor the involvement of divers (for underwater pressure gauges).

This report presents results from a radar gauge provided to the Proudman Oceanographic Laboratory (POL) by the OTT company for use at a test site at Gladstone Dock, Liverpool in NW England. Liverpool is a demanding location for testing a radar gauge with a tidal range of almost 10 m at some spring tides. Therefore, for a successful test, the radar range measurement has to be shown to be equally precise over distances of several metres to over 10 m. OTT is a long-established tide gauge manufacturer and, while it is not the only company manufacturing radar gauges, it is one with which most sea level authorities would be familiar. The gauge was a Kalesto which is a compact instrument which transmits FMCW radar pulses within a ± 5º cone, with a range accuracy claimed by the manufacturers to be ± 1 cm over a measuring range of 1.5 to 30 m. If this accuracy were to be verified, then the gauge would be a suitable candidate for use in many applications, including within the Global Sea Level Observing System (IOC, 2002).

The reference tide gauge chosen was a bubbler pressure system, being one of 44 such gauges in the UK National Network (Woodworth et al., 1999).

The advantages and disadvantages of bubblers are well-known (Pugh, 1972, 1987; IOC, 2002). Their main disadvantages, as for all pressure gauges, are the need to know well the density of the sea water above the pressure point (Figure 1), and to identify any long term drift in the pressure measurements, which in this case are performed by a differential (compared to atmospheric pressure), temperature-corrected Paroscientific Digiquartz transducer. Although Gladstone Dock is located at the mouth of a river (Mersey), the estuary is usually well-mixed. Surface water density is estimated to change by only ± 2 ‰ during a typical tidal cycle and by a similar amount seasonally (Sharaf El Din, 1964; Gilligan, 1968; Prandle et al., 1990), although much larger excursions are observed at times. Any drifts in the differential pressure (i.e. sea level) measurement are monitored by a variant of the 'mid-tide pressure sensor' method involving the use of a second bubbler pressure point at approximately mean sea level (Woodworth et al., 1996).

The radar gauge was installed at Liverpool in March 2002 and operated until the end of April 2003 without any important gaps. Almost all gaps in the time series shown below stemmed from outages in the bubbler record. A sampling interval of 15 minutes, which is the standard interval for all gauges in the National Network, was chosen for the radar so as to be compatible with the bubbler. Within the 15 minute interval, the two gauges determined average sea level in different ways. The bubbler performed continuous integrations of sea level within the 15 minute intervals, centred on the hour, 15 minutes past the hour etc., while the radar gauge provided 40 estimates of sea level within a 17 second window for each minute and then averaged the 15 one-minute values. If there is no significant sea level variability within the 15 minutes, then the two sets of sampling should in principle result in similar averages. Unfortunately, the 15 minute intervals selected for the radar gauge were not the same as for the bubbler, but were offset by approximately 7.5 minutes. For our data comparisons, this necessitated a resampling of radar data values by means of interpolation between measurements in order to derive radar values at the bubbler times. This will have introduced a small amount of interpolation noise into the comparisons.

Effective Density Considerations

In a comparison exercise such as this, the systematic errors of the reference system have to be considered in as much detail as those of the test system. The main systematic error for the bubbler concerns an assumption for the value of the product of average effective density of sea water and local acceleration due to gravity. This value is then used to convert the pressure measurements into sea level. The effective density used for operational purposes at Liverpool during 2002-2003 was

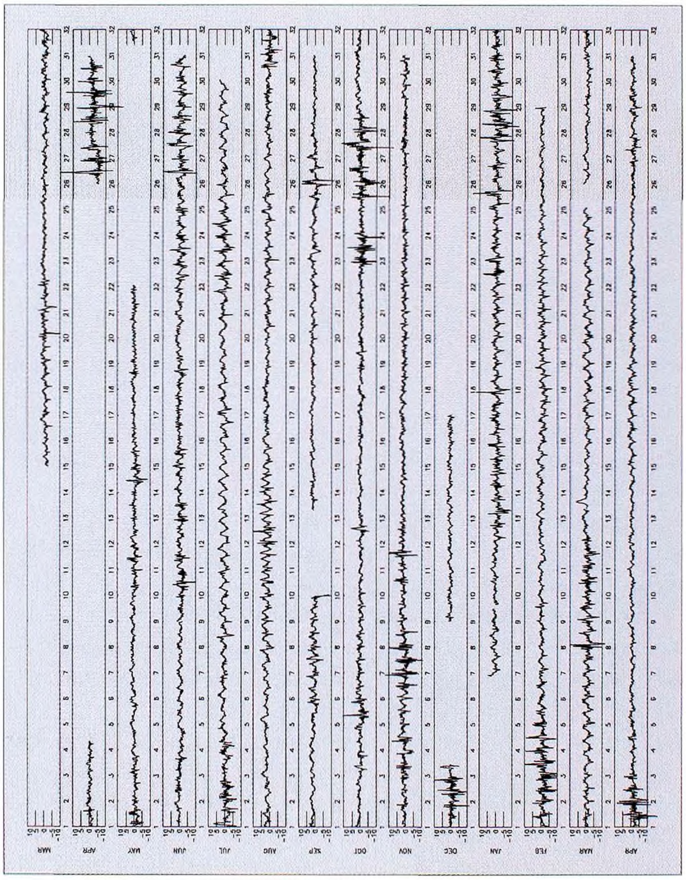

Figure 3: Time series of radar minus bubbler sea level difference from March 2002 to April 2003. Vertical scale ± 10 cm

set to approximately 1.026 g/cc which experience and occasional spot measurements during the year suggest was larger than the average density by approximately 4 ‰ (e.g. Sharaf El Din, 1964). In addition, a 'static correction' which is normally required to be applied to bubbler data (Pugh, 1972) was not allowed for, which has a consequence that the average effective water density will have been overestimated by an additional 3‰.

Consequently, one estimates that the average effective density used in determination of the sea levels of the reference data set was overestimated by approximately 7‰. This will have been compensated for to some extent (perhaps by 2‰) owing to the fact that density at the site varies throughout the tidal cycle, with largest values at high water (Prandle et al., 1990). Nevertheless, it can be seen that a scale error difference between the test and reference data sets of order 5-7 ‰ could be anticipated.

	Radar		Bubbler	
Tide	H (cm)	G (deg)	H (cm)	G (deg)
Sa	7.1	233.3	6.6	239.4
Ssa	7.3	121.8	7.5	121.4
Mm	2.9	230.7	2.8	229.0
Msf	1.1	89.8	1.3	77.1
Mf	2.0	153.6	2.1	150.2
O1	12.2	38.4	12.1	38.5
K1	12.4	189.2	12.3	189.2
M2	305.9	320.4	304.0	320.5
S2	98.9	4.1	98.2	4.2

Table 1: Tidal constituents (amplitude H and Greenwich phase lag G) determined during 2002-2003 from Liverpool radar and bubbler data. The POL convention for the phase lag of Sa has G=0 corresponding to the spring equinox (Pugh, 1987)

Data Comparisons

The radar and bubbler sea level time series span over a year and provide an excellent empirical measure of the suspected scale error. Linear regression was used to estimate the dependence of the difference between radar and bubbler level on radar (or bubbler) level itself. This yielded a constant of proportionality of 0.0064 which is consistent with the estimated scale error given above for the bubbler. In other words, if the scale error is entirely due to the bubbler, then for each cm of sea level variation measured by the radar, the bubbler will have measured 6.4‰ less because of the overestimated density times gravity. This clearly cannot exclude the possibility of the radar having its own scale error at the 1-2 ‰ level.

After empirical adjustment for the scale error, a time series for sea level difference was obtained as shown in Figure 3. This record of 15-minute differences has a root-mean-square (rms) value of 1.50 cm for the whole year (excluding outliers larger than ± 5 cm), while combination of 15-minute values into hourly differences reduces the rms to 1.41 cm. The series can be seen to contain short periods of large positive and negative excursions, such as at the end of April and the end of October 2002, when moderate storm surges of approximately 0.5 m occurred. In addition, evidence for tidal signals in the differences can be seen during June-September 2002 when the clock of the radar gauge was known to have been in error by up to 65 seconds. Although attempts have been made to estimate and correct the clock error, they may not have been made perfectly. Other tidal signals with an amplitude of approximately 2 cm are evident during February and March 2003 at times of very high spring tides, which one suspects represent real differences between the gauges because of density changes during the periods of the highest tides. Further clock errors would also manifest themselves in this way, although after the errors in summer 2002 more care was taken by OTT to ensure precise timings.

From inspection of the power of the high-frequency non-tidal residuals in the individual radar and bubbler time series after tidal variations had been removed by means of harmonic tidal analysis, we concluded that the high-frequency noise in both systems is of a similar magnitude with the radar slightly noisier than the bubbler gauge during storms (discussed further below). Consequently, we may tentatively divide the 1.50 cm rms sea level difference by $\sqrt{2}$ in order to estimate the time series precision of each system. This suggests that both systems can provide time series of approximately 1 cm precision which is consistent with Global Sea Level Observing System

(GLOSS) standards (IOC, 2002).

While the precision of a tide gauge time series is an important consideration, it is essential that sea level measurements have acceptable absolute accuracy with respect to a land datum, and that the accuracy is maintained from deployment of one gauge to another, as happens at any tide gauge site over many years. This is especially important if one aims to measure long term changes in sea level of order 1-2 mm/year over many decades (Church et al., 2001).

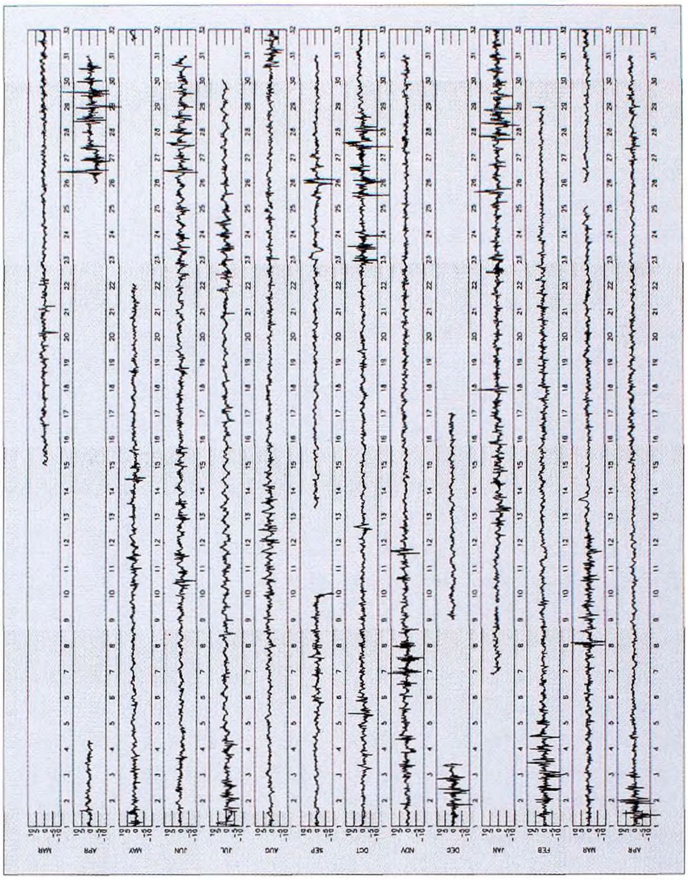

Figure 4: Time series of radar minus bubbler residual-differences. Vertical scale ± 10 cm

In the case of the Kalesto gauge, the recommended normal procedure to determine the absolute accuracy of the radar measurement is to undertake laboratory checks of the range from a reference mark on the radar unit to a target (e.g. a metal plate) which substitutes for the sea surface. If the measured range between the reference mark and the target plate is found to be offset from the real range, then a correction can be readily made within the gauge's electronic data logger. Such checks are considered to be relatively straightforward as the instrument can easily be detached temporarily from its installation and taken to a laboratory for checking, with such checks performed at typically yearly intervals. Once any systematic errors in range measurement are corrected, then the determination of the datum of the sea level measurements is simply a matter of geodetic levelling from land benchmarks to the reference mark on the unit.

Although the datum checks described above are straightforward, a more approximate ad hoc procedure was followed in the Liverpool experiment. In this case, the datum of the radar measurements was adjusted to be the same as that of the bubbler on the day of the radar installation in March 2002 by comparison of radar and bubbler measurements during a period between low and mid-tide, and the radar datum was not adjusted thereafter. A comparison of one gauge to another over a short period, with an assumption that the datum of the reference gauge is correct, is clearly a poor method of datum setup and is not the way we would operate with another new radar installation. A check on any drift in the datum of the systems can be made by calculating the trend in radar minus bubbler height (the latter corrected for scale error) through the year. This yielded a trend of -0.51 cm/year, which could be caused partly by changing density in the river through the year, given that our test lasted for only one year (see discussion of tidal constants below). If the drift was observed over a much longer period than a year, it would indicate an important failure to maintain datum over an extended period in one or both of the systems.

Tide and Surge Considerations

Table 1 shows some of the main tidal constituents determined from the radar and bubbler gauges during the experiment, using periods of data for which information from both sensors are available. The main diurnal and semidiurnal tides can be seen to be almost identical, with slightly larger amplitudes in the radar data as expected from the scale error discussion above. The long period tides are also the same at the millimetre level. An exception is the annual constituent (Sa) for which the amplitude differs by 0.5 cm. This could reflect to some extent the small seasonal changes in density in the river. Given that we have only a one year dataset, the change in Sa and the drift in radar minus bubbler height discussed above are alternative parameterisations of the same feature of the data.

A major objective of the comparison was to study how well the radar gauge functioned in providing residuals from a tidal analysis of their sea level data for comparison to surge predictions derived from the UK operational numerical surge model, as a main purpose of the National Network is the provision of sea level data for warnings of possible flooding as a consequence of winter storm surges. The year contained several surges, in particular around 26-30 April, 27 October and 1-2 December 2002 and 17 and 27-28 January, 2-4 February and 1-2 April 2003. Surge heights obtained from the model were approximately 0.6 m (the October surge being approximately 1.5 m), and the storms themselves were probably intense enough to enable general conclusions to be drawn on the ability of the radar to function during bad weather. However, there were no big surges comparable to those which occurred at Liverpool on several occasions during the 1990s (Woodworth and Blackman, 2002), which would have provided an ultimate test of the system.

The time series of residuals from the two analyses were found to be almost identical throughout the year, with the radar gauge describing surge levels as well as the bubbler. The time series of radar minus bubbler residual-difference (Figure 4) was found to be almost identical to that of sea level difference, but with the tidal signals in the time series much reduced. This is a consequence of any small differences between the tide observed by the two sensors being absorbed within the separate tidal analyses by means of small differences in the minor constituents. Unlike the sea level differences, the residual differences demonstrate zero secular trend, the drift discussed above having been absorbed into the annual tidal harmonic, and have an rms of 1.28 cm (excluding outliers larger than ± 5 cm), while combination of 15-minute values into hourly differences reduces the rms to 1.15 cm. From the perspective of validating the radar gauge, this suggests a sub-cm time series precision for the radar, slightly better than inferred from the sea level differences.

The storm-related fluctuations in sea level difference and residual difference were found to be almost identical. Some of these fluctuations look like 'noise' and are represented as large spikes or dips in Figures 3 and 4. However, as the fluctuations are mostly at the several cm level and rarely more than 5 cm, they are of little practical importance in terms of the provision of a comparison data set for present day surge models, in which predictions of surge height tend to be accurate at only the decimetre level (Flather, 2000; Williams and Flather, 2000). In addition, some of the fluctuations will be related to the different 15 minute sampling intervals employed in the test, rather than to intrinsic noise in either system.

A more serious issue concerns fluctuations which persist for several hours. There are several examples of such events, which are mostly negative and of the order of 5 cm and seem to have preference for occurring around high rather than low tide. The only extended period of negative fluctuation can be seen after the break in the time series at the end of April 2002, and is also of the order of 5 cm.

One particular concern is possible wave bias in either or both records. It is obvious that during storm surges, wave heights are likely to be larger than average. Bubbler data are known to contain a negative bias during high wave conditions, although the POL underwater pressure point is designed to minimise the influence of waves as much as possible. Any wave bias in the bubbler record will be more likely to occur at low water when the water depth is less (Pugh, 1972). The concern with radar gauges is whether their measurements are also biased low during high wave conditions if radar reflection takes place to a proportionately greater extent from wave troughs rather than crests. Such a bias is well-known in measurements of sea level from satellite radar altimeters (e.g. Chelton et al., 2001), although the two forms of radar measurement (frequency, antenna, range) are very different.

Waves were not recorded at the test site during the radar test. From nearby historical measurements (Draper and Blakey, 1969), mean significant wave height (Hs) in winter is known to be around 1 m, while Hs values over 2 m occur 10 per cent of the time and can exceed 3 m occasionally. From the combined available data, all that can be said at present is that, if there are negative wave biases in the records, then the radar must be biased more negatively than the bubbler by up to 5 cm. Further work on this aspect could involve wave measurements at the gauge site and a more complete understanding of the physics of the radar and bubbler measurements.

Conclusions

This report has described a comparison of radar and bubbler tide gauges at a test site near Liverpool in NW England where the large vertical range of the ocean tide, together with the frequent occurrence of storm surges in winter, places demands on the accuracy of gauges through a large range of sea level, during different sea states and weather conditions and with varying sea water density. The comparison took place over a period of just over a year, the minimum period for a useful comparison, and resulted in as much being learned of the bubbler (reference) system as the radar (test) system.

From the available data, we conclude that the radar appears to function as well as the bubbler most of the time, but that it produces a slightly noisier data set, with a possible bias of several centimetres compared to the bubbler during storms. If radar gauges are to be used elsewhere in the National Network or in GLOSS, we recommend that further work be undertaken to understand greater the different systematic biases, especially those due to waves, and to water density when the gauges are to be located near to rivers. There is also a requirement to develop an in situ calibration system for the radar gauge, removing the need for periodic laboratory calibration checks on range stability. Further insights into these technical challenges might stem from collaborative work presently being undertaken within the GLOSS and European Sea Level Service (ESEAS) programmes.

Figure 2 illustrates that radar gauges offer advantages over some other types of gauge with regard to ease of installation and maintenance. However, these features could present drawbacks in certain locations, if sites are exposed to harsh environmental conditions or if there are site security problems. Therefore, they may not be suitable for all locations, even if they prove to have acceptable ($\leq$ 1 cm) accuracy over long periods. Their merits and demerits compared to other systems (IOC, 2002) remain to be seen.

Acknowledgements

We would like to thank David Jones and Peter Foden of POL and Nigel Grimsley of OTT Hydrometry Ltd. for their help with this project.

References

Chelton, D.B., J.C. Ries, B.J. Haines, L-L. Fu, and P.S. Callahan. Satellite altimetry. pp.1-131 in, *Satellite altimetry and earth sciences.* A handbook of techniques and applications (Fu, L.-L. and A. Cazenave, eds.), Academic Press, San Diego, 2001

Church, J.A., J.M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin, and P.L. Woodworth. Changes in sea level. In, Climate Change 2001: *The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. (eds. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson). Cambridge: Cambridge University Press. 881pp, 2001

Draper, L., and Blakey, A. *Waves at the Mersey Bar light vessel.* National Institute of Oceanography, Internal Report No. A.37, 1969

Flather, R.A. *Existing operational oceanography.* Coastal Engineering, v. 41(1/3), pp. 13-40, 2000

Gilligan, R.M. *Circulation and mixing in the Mersey Estuary.* Ph.D. thesis, University of Liverpool, 1968

IOC. *Manual on sea-level measurement and interpretation.* Volume III: Reappraisals and recommendations as of the year 2000. Intergovernmental Oceanographic Commission, Manuals & Guides, No 14, 47pp. & appendices, 2002

Pugh, D.T. The physics of pneumatic tide gauges. *International Hydrographic Review,* v. 49, pp. 71-97, 1972

Pugh, D.T. *Tides, surges and mean sea-level: a handbook for engineers and scientists.* Wiley, Chichester, 472pp, 1987

Prandle, D., A. Murray, and R. Johnson. Analyses of flux measurements in the River Mersey. *Coastal and Estuarine Studies,* v. 38, pp. 413-430, 1990

Sharaf El Din, S.H. *The circulation and mixing processes in the River Mersey and the Irish Sea.* Ph.D. thesis, University of Liverpool, 1964

Williams, J.A., and R.A. Flather. *Interfacing the operational storm surge model to a new mesoscale atmospheric model.* Proudman Oceanographic Laboratory Internal Document No. 127, 13pp & figures, 2000

Woodworth, P.L., J.M. Vassie, R. Spencer, and D.E. Smith. *Precise datum control for pressure tide gauges.* Marine Geodesy, v. 19(1), pp. 1-20, 1996

Woodworth, P.L., M.N. Tsimplis, R.A. Flather, and I. Shennan. A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysical Journal International*, v. 136, pp. 651-670, 1999

Woodworth, P.L., and D.L. Blackman. Changes in extreme high waters at Liverpool since 1768. *International Journal of Climatology*, v. 22, pp. 697-714, 2002

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