

**SEA LEVEL INSTRUMENTATION,
ITS LIMITATIONS AND THE OPTIMISATION OF THE PERFORMANCE
OF CONVENTIONAL GAUGES IN GREAT BRITAIN**

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PREAMBLE

It is perhaps appropriate that a new term "Coastal Geodesy" has been coined to describe the science which concerns this Symposium. The use by geodesists of sea level observations is not new, neither is the use of land datums by oceanographers, but only in recent years has there developed an awareness by both parties of the problems faced by the discipline as a whole. This is particularly true of oceanographers since in two major respects a clarification of the difficulties has recently emerged. In the past there has been a ready acceptance of a national geodetic reference plane with which to associate sea levels. This has been unwise since such a plane is an ephemeral concept based upon uncertainties of instruments, procedures and statistical adjustment, all of which change in time. There is nothing stable or tangible about a reference plane. Again, oceanographers have begun to assess the performance characteristics of their own traditional instruments and have been alarmed at what they have found. This matter is particularly serious in a discipline which requires the use of long time series, since it means that available data must be viewed with suspicion. The problem is compounded by the realisation that, as yet, we have found no solution to many of the instrumental inadequacies.

As in many geophysical problems we may be concerned with absolute values or with variations about a mean, the latter usually being more amenable to study. In coastal geodesy, for example, an exercise might be involved with variations in space of land or sea levels or both. Alternatively, the object may be to establish variations in time at a single loca-

tion. The basic aim of the discipline, however, must be to relate land and sea levels both in time and space and this may not prove to be generally possible at present. Bearing in mind the fact that not always can much be done to make past records more meaningful, we can at least address ourselves to the future and attempt to optimise upon our instrumental ability and experience in order to improve the data which will become available to the next generation of coastal geodesists.

A review of the present situation and apparent possibilities may be attempted under a variety of headings as follows.

SITING

In the past little regard has been given to the siting of tide gauges for our purposes and we have been forced to utilise instruments installed for quite different reasons, usually associated with port operation or navigation. Tide gauges tend to be installed predominantly in estuaries, with consequent problems arising from variations of salinity and temperature and from river flow, or else in harbours and enclosed areas which may possess inherent anomalies of level with reference to open water. Again, due notice should be taken of the phenomenon of energy transfer through the presence of surface waves which has come to light in recent years through theoretical investigations by LONGUET-HIGGINS and STEWART [1] and practical experiments by BOWEN, INMAN and SIMMONS [2]. It may be impossible to find a tide gauge site which is perfect in all respects but most present sites do seem to be associated with maximum "noise" from the point of view of long period phenomena. A solution would seem to be to seek new open coastal sites, paying due regard to any irregularities of the sea bed or other coastal configurations which might contribute local anomalous levels, and only if the problems of exposure to surface waves can be overcome. To anyone who has conducted a reconnaissance for a tide gauge site and has appreciated the paucity of possibilities where a vertical drop into deep water is available, the problems seem immense. One can only effect a compromise but it is essential to conduct a thorough research exercise into all phenomena likely to affect sea levels at the site, so as to be aware at least of local problems and to conduct an appropriate programme of observation of all relevant parameters.

INSTRUMENTAL PRECISION

Presented with an instrumental site it is extraordinarily difficult to achieve a record of sea level variations with a precision adequate for the discipline. The basic recording instrument has remained virtually unchanged for decades. It comprises two devices, the stilling well and the recorder, each of which possess inherent failings. Only in recent years has this

arrangement been examined critically so that the appropriate response functions can be evaluated, for example in LENNON [3].

A. The Stilling Well

The most serious problems arise in the necessity to adopt a physical filter for surface waves in the form of a vertical tube which is connected to open water through a small orifice or pipe. Environmental problems of weed, trash, marine growth and siltation immediately arise so that the characteristics of the designed filter cannot be maintained. A paper by SHIPLEY [4] examined the physics of the stilling well system and his work was further developed by ROSSITER and LAL [5] so as to include the attenuation of short waves due to the depth of the orifice below the water surface. A more rigorous mathematical study by NOYE [6] considers the response function of a tide well which has a long pipe connecting it to the sea and it is shown that such an arrangement can behave as a linear device which responds with oscillations of the same frequency as the sea level in a manner which is independent of amplitude. This is clearly more attractive than the normal non-linear system based upon an orifice. For tidal investigations such matters are critically important but fortunately in the low frequency spectrum, in which lies the interests of coastal geodesy, they cause little concern unless we heed the warning of CROSS [7] who, in an investigation of flow through a well orifice finds it asymmetrical. He postulates that well levels might be subject to a pumping-down effect at times of significant surging outside the well, perhaps by as much as 15 cm in the presence of waves 1.5 to 3 metres high.

It is important to remember that the stilling well is a pressure device whereby an equilibrium is sought between pressures imposed at the orifice by the water head inside and outside the well. Any phenomenon which affects this balance is therefore a threat and, in fact, we are aware of at least two such sources of perturbation. In the first place, estuarine sites are invariably associated with salinity and temperature changes of tidal period so that the water sample contained within the well is seldom compatible in its density with the open water and then only at low tide. The well is usually stratified, with low density water associated with low tide conditions in the upper part of the well and higher density water associated with higher tidal levels in the lower sections of the well. The error involved can be significant and since it depends both upon the differential of the depth mean densities of the two water heads and also upon the height of the column above the orifice, it is asymmetrical in character and increases appreciably in the vicinity of high tide. Tide gauges in the River Mersey, for example, where the tidal range is of the order of 10 metres and where depth mean densities can vary by 0.7%, can show errors in excess of 6 cm at spring high water, levels within the well of course being higher than the open water at this time (see LENNON [3]). A second effect, perhaps more serious in its implications, is found in turbulence generated in the stream flow of the external water particularly by obstacles and projections in the vicinity of the gauge. The tubular

stilling well, which is free standing or else is strapped to a river wall, is particularly prone to this effect especially if it is of the single basal orifice type. Laboratory experiments by PERRY at Liverpool University, later supported by field measurements on actual gauges, showed the danger of an alarming drawdown of well water associated with maximum tidal streams near to half-tide. Reference is again made to the effect in LENNON [3] but is discussed in detail by HALLIWELL and PERRY [8] and [9]. As in the case of the salinity error, the effect is to give a systematic effect, this time a shortfall in recorded mean sea level such that streams in excess of 1/2 knot would give unacceptable results. Although the modern tubular well with orifice is prone to this error, all gauges are susceptible. Carefully sited pipes are to be preferred to orifices and perhaps a pipe opening in a smooth wall is the best, but unfortunately most expensive, solution.

An inescapable conclusion therefore is that the stilling well system is highly suspect as the basis for any sea level records for use in coastal geodesy unless all perturbing factors are known and monitored. Consequently a recording instrument which can operate without the assistance of the stilling well is of high priority.

B. The Recording Instrument

Given a stilling well with its faults, it is still not a simple matter to record its internal water level with the desired accuracy if tests on existing instruments are to be taken as a guide. Most instruments show a lag in their response to level changes but in the investigation of long period phenomena this is of negligible consequence. A surprising number of common faults, however, do occur which are systematic in our context and arise from riding turns in float or counterpoise suspension, or perhaps in the pen carriage drive, inconstant tension in the float suspension and, particularly in the analogue type gauges, poorly drawn graticules combined with humidity effects on paper charts contribute large errors. Fortunately, a checking procedure is easily possible using a sounding probe from the well-head and sensing contact with the water, using an electrical continuity circuit. An accuracy of ± 2 mm can be achieved. The use of such a probe in a 13-hour programme which establishes the tide gauge error at all states of rising and falling tide, the Van de Castele Test, has been adopted as a routine procedure in the U.K. for some years and has proved an invaluable means of identifying and diagnosing tide gauge faults. These matters are discussed in detail in LENNON [10]. It is possible to associate certain inherent faults with particular present day gauge designs or with particular modern manufacturers. To effect corrections in a mean sea level time series extending over many years, however, is not generally conceivable in view of the short life span of an instrument and the consequent changes in the instrumental response function which will have occurred. Moreover, what is common to most site investigations is the instability of performance and the multiplicity of faults which appear and disappear in response to random maintenance. The digital tide gauge which produces a record usually in punched paper tape at a discrete sampling interval is usually

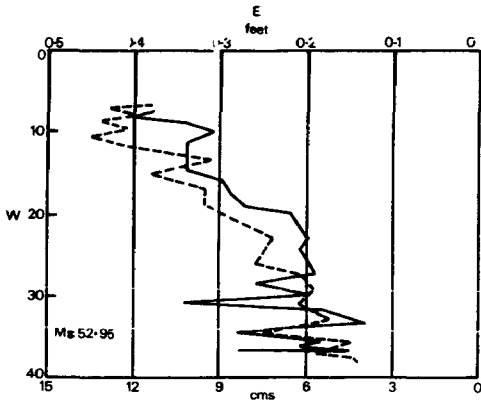
found to have an accuracy of level measurement one order better than the analogue gauge, simply due to the freedom it has from the faults associated with the manufacture, storage and fitting of analogue charts. Figure 1 shows the recent performance of an average analogue gauge on the basis of a series of Van de Castele tests, which it must be remembered are merely spot checks at widely spaced intervals. In addition to the random faults which appear it is clear that a common calibration fault exists. In the lower right of figure 1 the series of tests are synthesised in a plot of mean tide gauge error against the elevation of the water surface in order to emphasise this inherent fault. Whether or not faults of this type are significant in the interpretation of mean sea level depends of course, upon their form but also upon the procedures adopted locally for adjusting the instrument. If adjustments are made in a random fashion, then all may be well. If adjustments are made at a fixed clock time each day then again the fault is not critical with regard to the lunar tide but some systematic error may be introduced through the solar tidal constituents. If, however, adjustments are made at a fixed tidal elevation then the contributed error could be serious. The case emphasises the uncertainty of tide gauge records for our purposes. If a regular record is kept, based upon Van de Castele tests and a close supervision of local practice, then it may be possible to salvage something from the series and this is the present philosophy adopted in the U.K. Such a solution can only be accepted as a temporary measure. The case for more reliable instrumentation is established beyond doubt.

Some improvement has already been made in the recording of well levels by the introduction of the digital tide gauge. At the Institute of Coastal Oceanography and Tides a programme of instrumental tests has been conducted over recent years. Figure 2 illustrates the performance of three digital gauges which have been examined over periods of a few months. Here are shown in fact Van de Castele diagrams which apply to the commencement and to the conclusion of the test period in each case. The diagrams confirm a near constant response function for each instrument and, moreover, of a quality vastly superior to that of the average analogue gauge. A word of caution is appropriate in the case of digital gauges since they normally sample water level discretely at a fixed interval irrespective of any short period oscillations within the well. Care is required to match the sampling interval to this environment if noise is not to be contributed through aliasing.

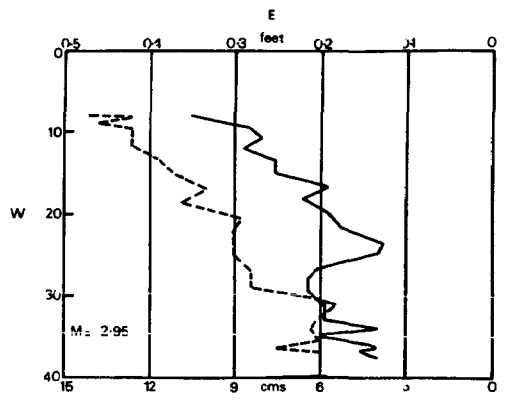
C. The ability to hold a stable datum

The faults summarised in A and B are concerned with errors which appear within the tidal periods and many of these fortunately disappear in the numerical treatment which is adopted to reduce the record to an estimate of mean sea level. What is more important in the context of this Symposium is the ability of a tide gauge to maintain a stable datum and this fact also is a combined function of instrumentation and operating procedure.

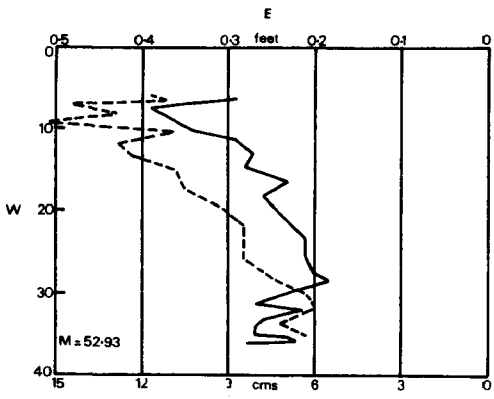
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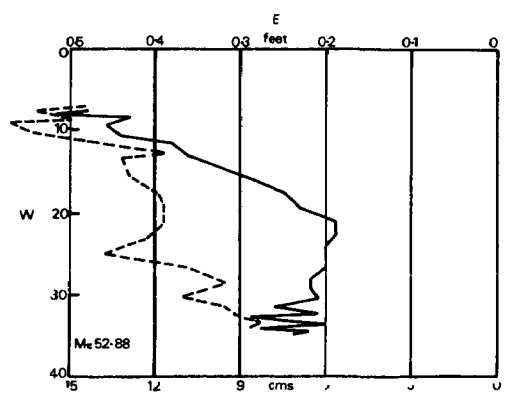
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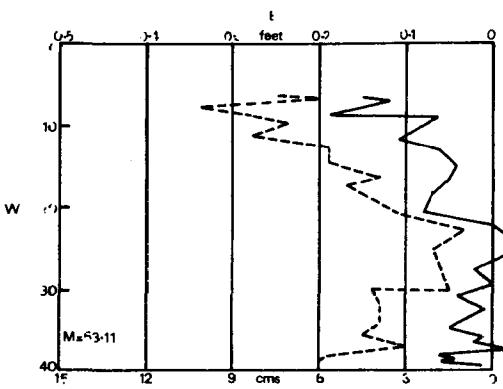
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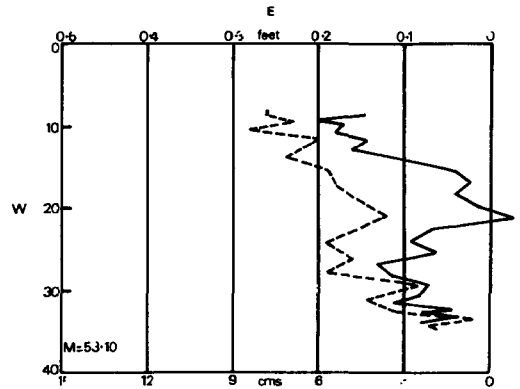
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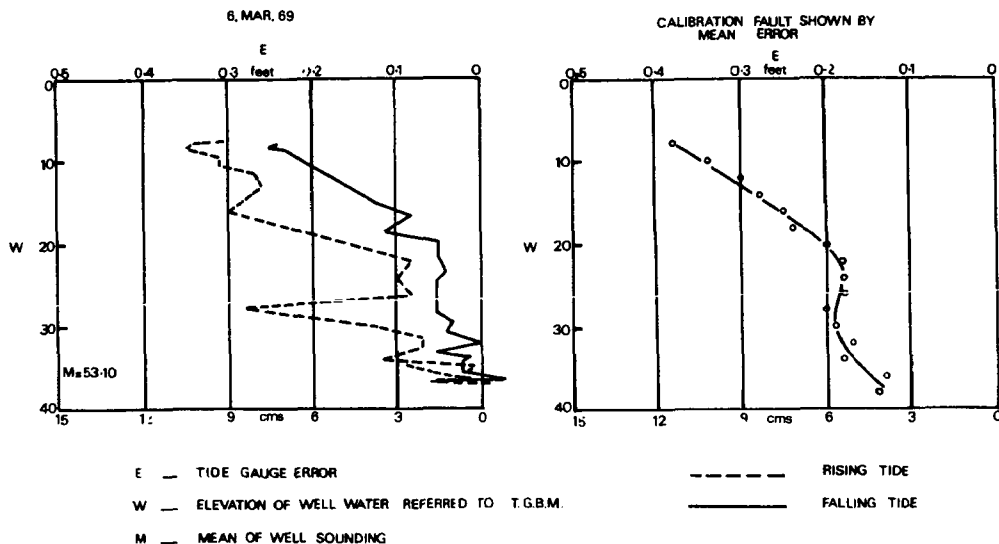


FIG. 1. — Performance stability of average analogue gauge from Van de Castelee tests.

It has been mentioned that analogue tide gauges are particularly poor in this respect due to instability of the paper medium and the necessity to transfer datum from one paper chart to another. The superiority of digital gauges is most marked. In figure 3 a comparison is made between the datum stability of an analogue gauge with respect to that of a digital gauge. In this case both instruments were installed in the same well and maintained by the same staff. The datum errors were established by weekly well soundings common to both instruments.

We have already established that tide gauge errors are partly due to the function of the stilling well and partly due to the inadequacies of the recorder so that it is important to remember that our aim should be to consider datum stability of the record with respect to open water. In this aim procedure is all-important. At the present time in the U.K. we have adopted a compromise solution whereby the tide gauge error in time and elevation is noted each day by reference to a visual tide staff set in open water in sight of the tide gauge hut. This, it is acknowledged, is far from ideal but in the interests of mean sea level studies it does attempt to average out errors from all sources. After defining the problems involved, it is envisaged that a second phase will soon be introduced whereby gauge errors will be determined by well soundings, which we have established are more accurate by at least one order of magnitude. Such a procedure, however, requires a knowledge of errors contributed by the stilling well and will depend upon a thorough survey of all factors affecting a tide gauge site and a more rigorous process of data reduction. An ultimate stage, still some years in the future, will, optimistically, be based upon a new generation of instruments, digital in type, which can function effectively in open water in the presence of surface waves.

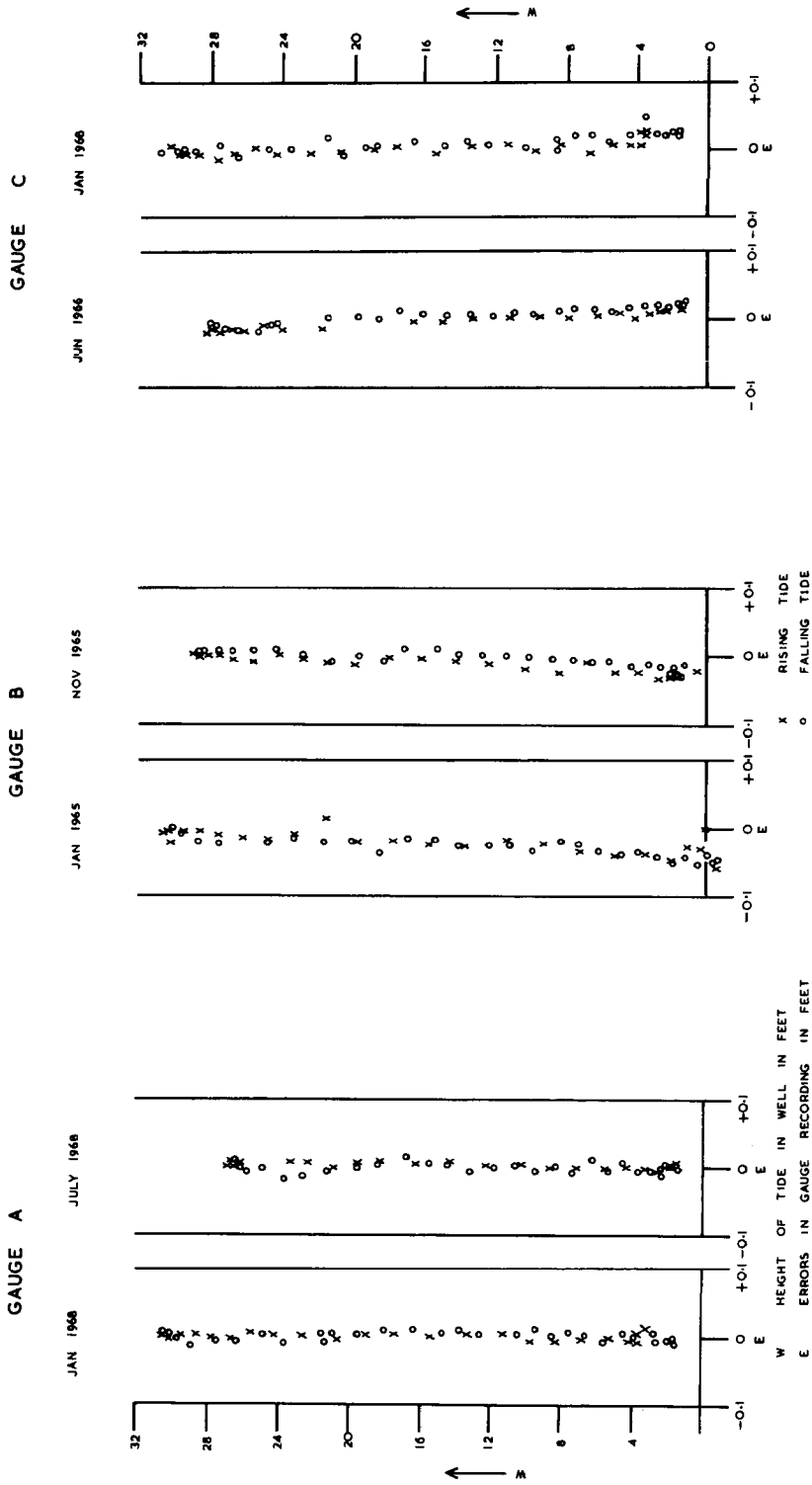


FIG. 2. — Stability of performance of digital gauges.

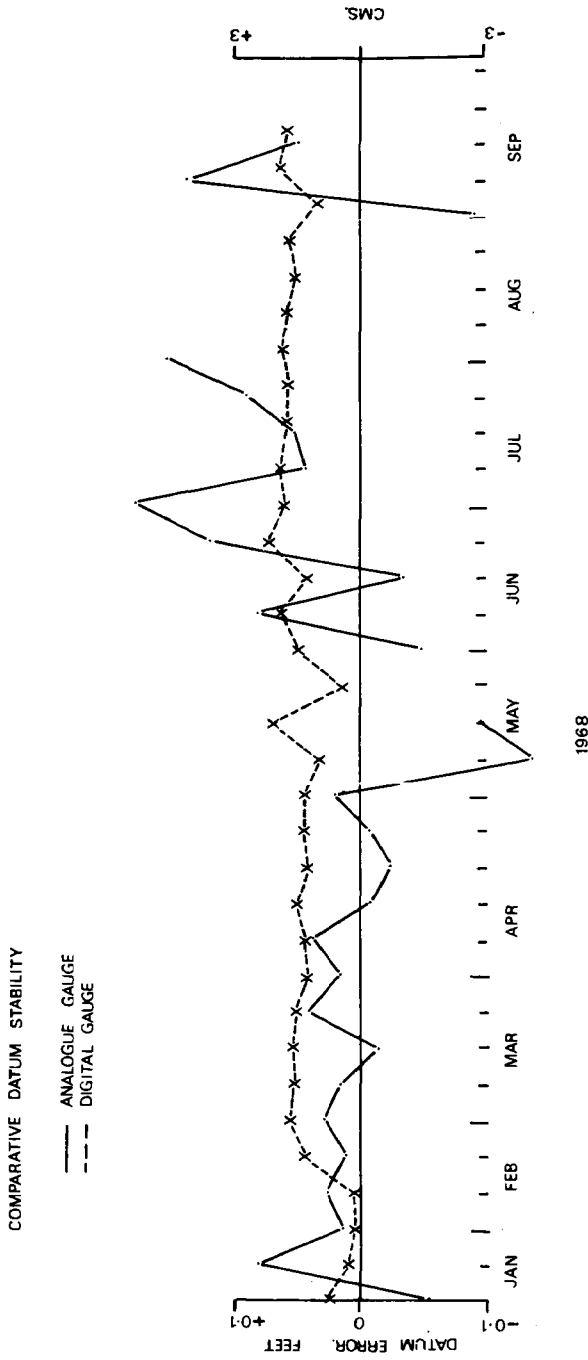
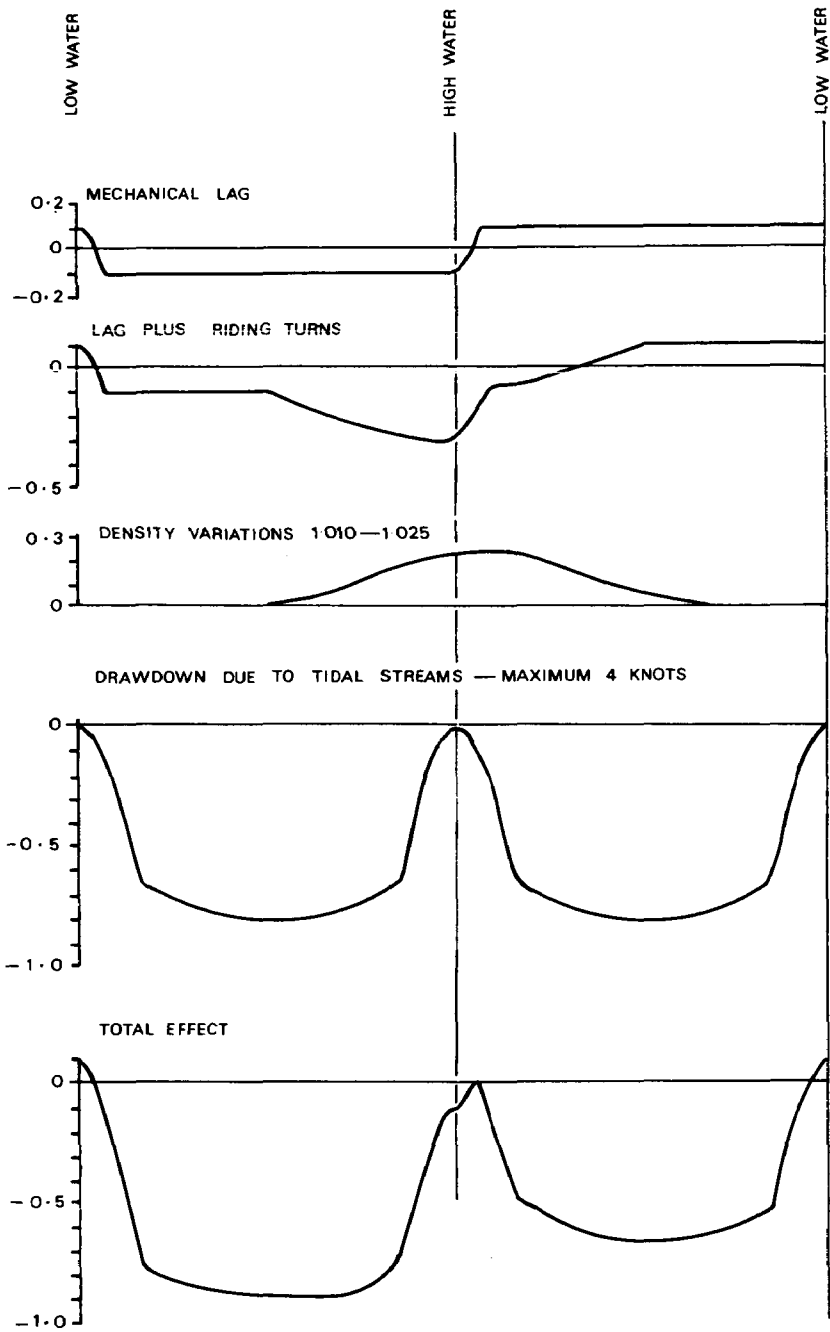


Fig. 3. --- Comparative datum stability.



BASED UPON SEMIDIURNAL TIDE OF 10 FOOT AMPLITUDE

Fig. 4. — Characteristic form of typical tide gauge errors.

D. The characteristics of tide gauge errors

It is informative to examine the more common tide gauge faults from the theory now available to us and to trace their effect within a tidal cycle. This is attempted in figure 4. Here a simple semi-diurnal harmonic is taken having an amplitude of 10 feet (approximately 3 metres). Assuming such a tide to exist in open water it was then postulated that attempts to record the oscillation were by tide gauges susceptible to certain typical errors already discussed. The corresponding errors are shown in the diagram as follows :

- 1) The usual effect of mechanical lag due to friction and/or backlash.
- 2) The same lag as before, with the addition of a calibration error of 2% which appears above mean sea level. This simulates a common tide gauge fault, namely riding turns in float suspension.
- 3) The effect on well levels resulting from density differences between enclosed and open water. Here the result is shown of density variations in the open water between 1.010 near to low water and 1.025 near to high water, similar to that observed in the Mersey Estuary. The time profile of density variation has also been taken from observations in the Mersey.
- 4) In order to simulate the drawdown in well levels due to streams in the vicinity of the well it is here assumed that we have a free standing tubular stilling well with a single basal orifice. The maximum stream is assumed to be 4 knots, a magnitude which can occur in the Mersey Estuary. The characteristics of stream time profiles are numerous but here has been adopted a typical river form.
- 5) Finally is shown the error curve arising from a combination of all the faults.

It might be imagined that such large errors would not escape notice. However in figure 5 is shown the comparison between the hypothetical open water tide and the curve which would be drawn by a gauge having all the above faults. It must be agreed that the latter differs in no obvious respect from many actual tide gauge recordings and is in no sense remarkable. The attached table proceeds further and examines the results of harmonic analysis of the errors shown in figure 4. In the first place the undisturbed tide is analysed, about a mean level of 10 feet, in order to test the analytical technique. This gives some assurance that analytical " noise " of the order of 0.001 is to be expected but that any result materially greater than this is likely to be significant.

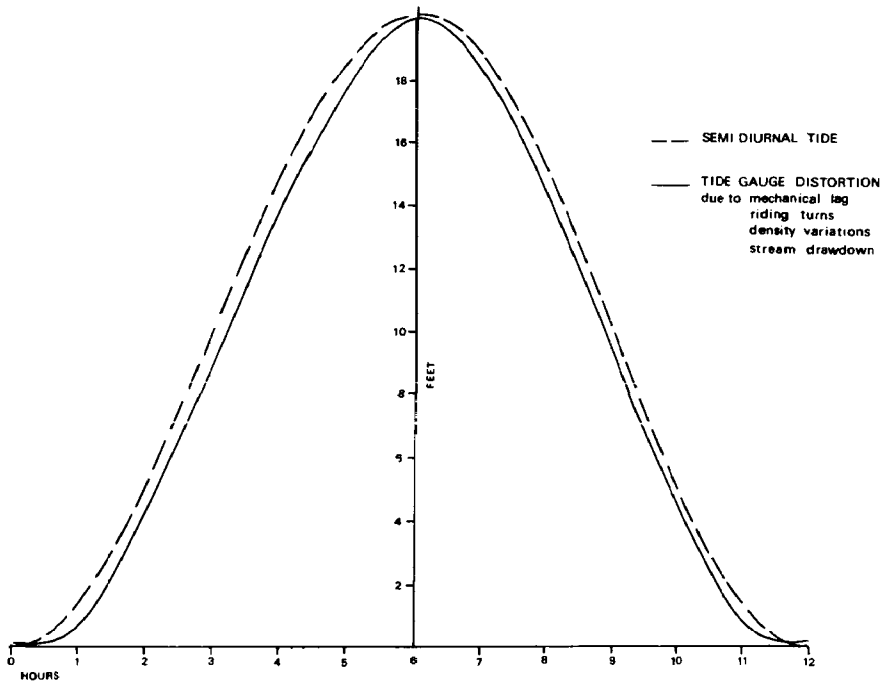


FIG. 5. — Comparison between the hypothetical open water tide and the curve produced by a gauge.

Harmonic Analysis of Typical Tide Gauge Errors Amplitude of Correction in feet

Species Number	0	2	4	6	8	10	12	14
Undisturbed tide	10.000	10.000	-	0.001	-	0.001	-	-
0.1 ft Gauge lag	9.999	9.983	0.002	0.043	0.001	0.025	0.001	0.016
Gauge lag plus riding turns effect	9.937	9.885	0.042	0.043	0.008	0.024	0.004	0.018
Density variation 1.010 to 1.025	10.076	10.100	0.036	0.011	0.004	0.005	0.004	0.002
Stream drawdown 4 knot maximum	9.399	10.000	0.322	0.001	0.168	0.001	0.096	-
Density variation plus stream drawdown	9.476	10.100	0.355	0.011	0.164	0.005	0.093	0.002
All above effects combined	9.420	9.986	0.315	0.049	0.175	0.024	0.092	0.018

Note : No response in odd species.

Also : 1 foot = 30 cm approximately.

In the interests of coastal geodesy, the entries under species 0 are most significant since these indicate the evaluation of mean sea level. However, all data reduction techniques must take due account of the existence of oscillatory phenomena in all species. The fact that all the even numbered species, semi-diurnal, quarter-diurnal, right up to the fourteenth diurnal contain significant contributions is therefore of note.

THE GEODETIC INTERFACE

The foregoing notes indicate those problems with which the oceanographer must contend in order to make meaningful conclusions from his observations. A different set of problems faces the geodesist in carrying land levels to coastal sites. What is of primary importance is that the procedures of both disciplines should allow an overall geophysical interpretation. It is suggested that the oceanographer should hand over responsibility to the geodesist in the near vicinity of the coastline and that this is best achieved by the selection of a particular physical reference point which is likely to have some permanence. In this we have a Tide Gauge Bench Mark to which the oceanographer should attempt to maintain the datum of his tide gauge in a fixed relationship. In practice this is achieved by frequent (6 monthly) levellings between the Tide Gauge Bench Mark and both visual tide staff, if employed, and a convenient contact mark within the tide gauge hut from which it is possible to effect soundings inside the stilling well. A degree of insurance against possible damage to the Tide Gauge Bench Mark is achieved by establishing a connection, at the same time interval, between this mark and other bench marks in the vicinity. It is not suggested that the Tide Gauge Bench Mark is necessarily stable but it is inferred that the responsibility for establishing the degree of stability of this reference point with respect to its near environment and with respect to the rest of the land mass is properly placed in the field of geodesy. Reliance upon a connection with a distant physical mark through a national or regional levelling datum is to be discouraged and is considered to confuse the general picture.

TIDE GAUGE PRACTICE IN THE U. K.

It is doubtful whether any country can be satisfied with its attempts to provide oceanographic data for coastal geodesy and certainly the state of the art in the U. K. at the present time gives little cause for complacency. The situation has however been improved in recent years by the establishment of a national Working Party on Tide Gauges which has now accepted responsibility for a national network of tide gauges around the coast. The instrumentation of sites is under constant review, approved publications specifying the requirements for instrument operation and maintenance have been prepared and each installation is subject to an inspection by the Ordnance Survey on two occasions each year. On at least one occasion each



FIG. 6. — Network of tide gauges used for mean sea level.

year a full Van de Castele Test is performed over a spring tide cycle. The service has recently been supplemented by the establishment of a supervisory team whose task it is to act upon the fault diagnosis made available by the above tests as a primary requirement, to keep a record of all relevant site and maintenance details and to establish a microfilm library of all observational records complete with appropriate annotations of day-to-day errors. In figure 6 are shown those gauges in the network which are assigned, though not exclusively, to mean sea level monitoring.

On the basis of the remarks in this paper we would recognise that we have inadequate instruments and many doubtful sites but the service now established is at least attempting to evaluate the problems which exist locally with a view to a more precise interpretation of observations in the future. The task of evaluating the design of each gauge in relation to its environment has begun and this includes stream and salinity measurements. The present policy is therefore to attempt to service a large number of mean sea level stations on the principle of an in-built redundancy. It is accepted, however, that a much more sophisticated system is required and with a minimum of delay.

A FUTURE AIM

The study of tidal instrumentation in the mean sea level context emphasises the constant battle against "noise". In recording the entire frequency spectrum in order to achieve meaningful results in a limited low frequency band we are faced with the necessity to consider all the perturbing factors from surface waves at one end of the scale, to residual wind effects at the other. In addition to the short-term instrumental effects considered earlier, the evaluation of secular trends for example requires attempts to remove long period meteorological, steric and residual stream "noise", which represents, in fact, real regional sea phenomena. The physical problem therefore seems to call for a degree of sophistication in observational techniques which has not yet been attempted. The complexity of the problem is such that may be unreasonable to expect to achieve a large array of monitoring stations of acceptable standard. A geographical unit of the order of size of the U. K. mainland might, however, expect to establish, say, 4 first-class stations all preferably in open coast sites carefully vetted so as to avoid anomalous regional effects. Here we might expect to find operational and standby sea level recorders which, hopefully, would be capable of achieving a high resolution even in the presence of surface waves. Instrumentation might be designed to monitor surface waves in addition to the familiar tidal spectrum, but more important perhaps is the requirement that all parameters contributing to noise should be monitored. It would be desirable, for example, to have continuous records of depth mean temperatures and salinity and/or pressure of the water head above a fixed datum as a means of estimating steric noise. Local wind and barometric pressures would provide desirable additional data. Such a possibility seems to hinge upon the development of an instrument which will give a high resolution of sea level measurement in the presence of waves.

A DIGITAL TIDE GAUGE WITH AN ELECTRONIC WAVE FILTER

This particular problem has been studied in some depth and recently a design and development contract has been negotiated with a commercial firm of electronic engineers. Already this company possessed considerable expertise in precise liquid level measurements in unusual environments, for example the measurement of inflammable liquid gases. In a protracted design study, and with joint collaboration, the specifications for a new type of tide gauge were established.

The sensor consists of a flexible plastic-covered "printed circuit" strip with active electrodes spaced at 2 cm intervals. Using a capacitance detec-

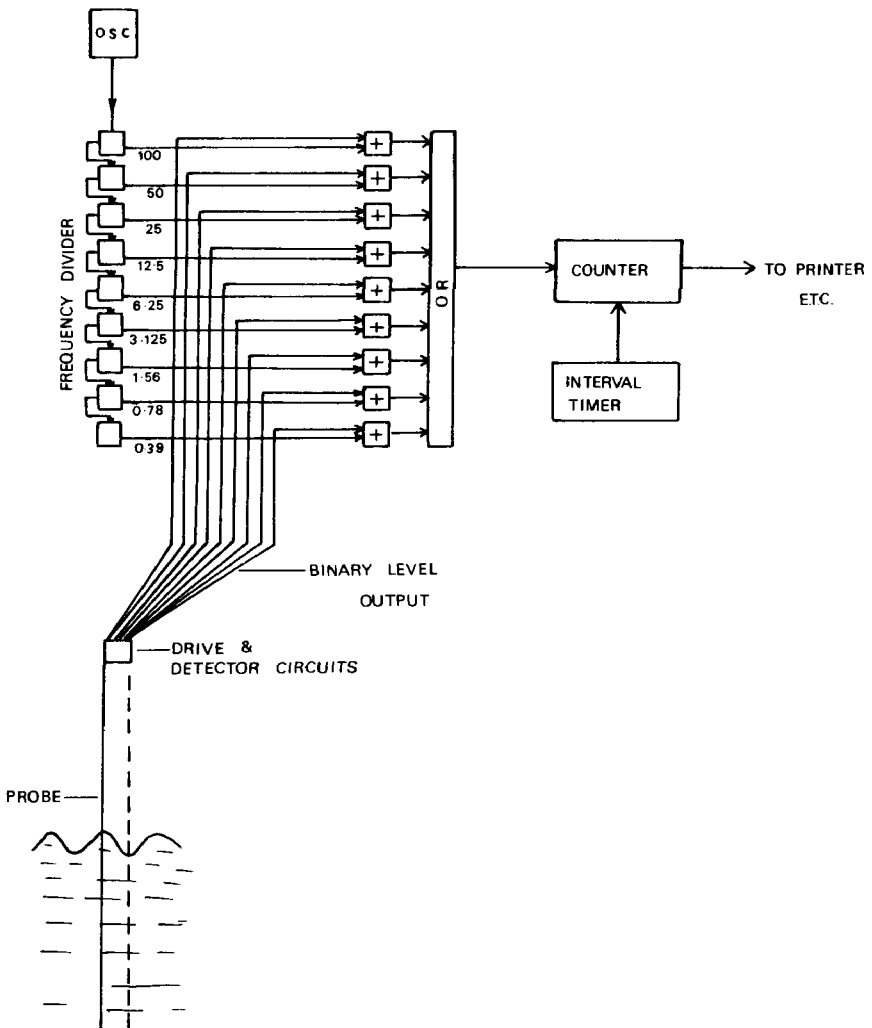


FIG. 7. — Simplified block diagram for a digital tide gauge with an electronic wave filter.

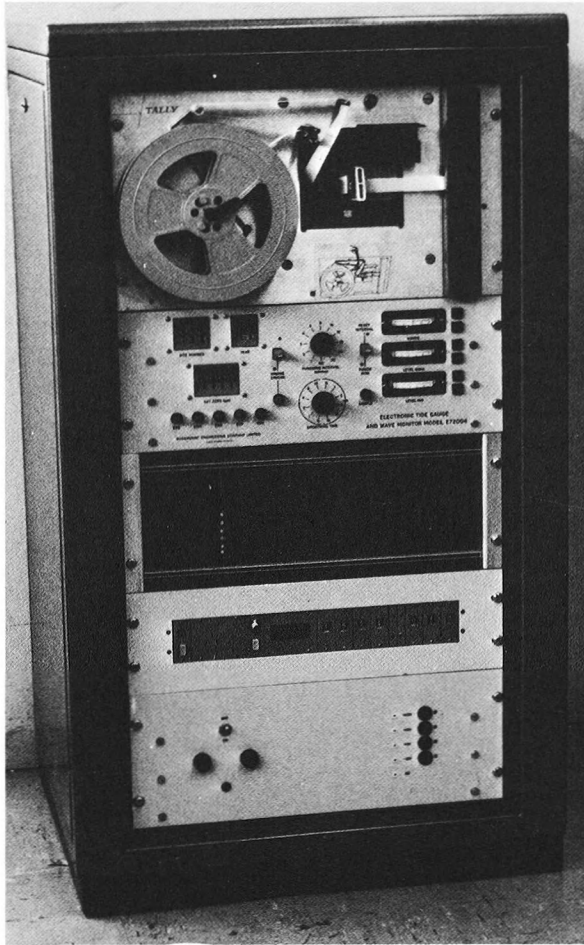


FIG. 8a. — Console of new electronic tide gauge.

tion system the instantaneous water level is measured to the nearest 2 cm, approximately every 50 milliseconds in an electronics unit mounted at the head of the sensor. A central electronics unit interrogates the sensor in order to receive the binary signal so generated. Each bit is then used to gate a pulse train of a frequency proportional to the bit. These binary-related pulse trains are arranged to be non-coincident so that the gated trains can be mixed together to form a single train whose pulse rate is proportional to the instantaneous water level. A continuous averaging system then accepts the measurement and combines it with an average of previous measurements to give a continuous "running mean". Full weight is given to the most recent measurement and exponentially less weight to earlier measurements. An optional time constant of the exponential is available so as to meet a variety of local conditions. Options range in 11 binary steps from 1/2 second to 16 minutes. The system is shown in a simplified diagrammatic form in figure 7. An unexpected bonus arises from the design in the following manner. The basic sensor has a discrimination of 2 cm and this is capable of little improvement in still water.

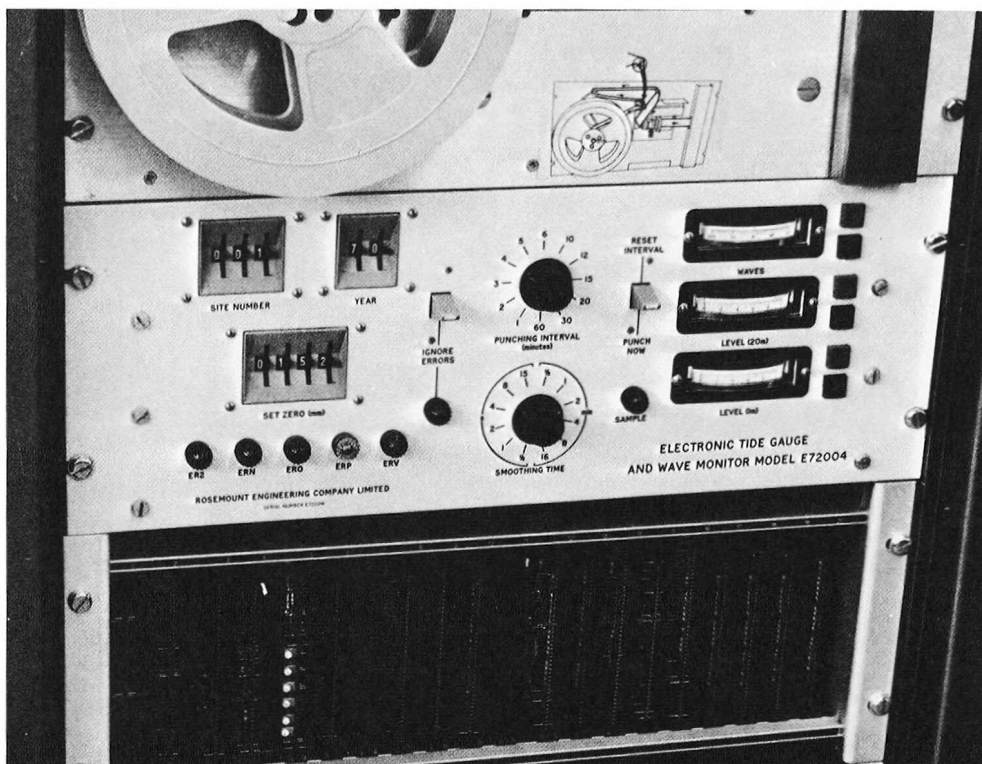


FIG. 8b. — Enlargement of part of the electronic tide gauge shown in figure 8.

In the presence of waves, however, the sampling procedure described above makes possible a higher resolution of measurement and the prototype instrument is designed to give an accuracy of the order of 1 mm in a range of 13 metres.

Some difficulties have arisen in the manufacture of the long length of printed circuit probe and these are at present being overcome. It is hoped that the instrument will be available for field trials before the end of 1970. Many tests must be performed before it is possible to accept such a new device operationally. It is clear that the efficiency of the sensor depends upon the extremely low water absorption and wettability properties of its plastic outer skin. The experience of exposure to a marine environment will therefore be somewhat critical for the future of the gauge. Until such feasibility trials are completed, the logging facilities of the prototype are relatively unsophisticated. However, the following features are included :

- 1) Sampling interval optional in 11 steps from 1 minute to 60 minutes.
- 2) A pre-set zero shift to be applied to each measurement so as to allow for calibration of the probe mounting relative to the approved datum.
- 3) Digital recording on 5-channel paper tape.
- 4) Additional analogue voltage output in three stages:
 - proportional to the instantaneous unfiltered measurement of surface elevation (for use in surface wave monitoring).

- Tidal elevation (filtered output) in a range 0-20 metres with a precision of $\pm 2\%$.
 - Tidal elevation as a proportion of appropriate integral metre in above range with a precision of $\pm 2\%$.
- 5) Automatic printing on output tape of instrument serial number, year, day number and time.

Considerable store is set on the future of this instrument, or on instruments like this, capable of operation in the exposed marine environment and consequently free from the troubles which have beset tidal instrumentation to date. It is a sobering thought to reflect upon the time interval required to allow such new instrumentation to make a contribution to coastal geodesy.

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