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Waves, surges and tides

David Cartwright

Experiments with the Shipborne Wave Recorder

I was recruited by the Royal Naval Scientific Service (RNSS) in 1951, with a mathematics degree and a love of the sea, but I was assigned to a branch of the Admiralty near Bath known as DNC (Department of Naval Construction), which designed the construction of naval ships. I turned out to be a misfit in the hierarchy of DNC, and after two years I started desperately to look for other openings within the RNSS. I was particularly attracted by the *Reports on Wave Research* issued by Group W of ARL, and saw ready applications of their ideas and methods to outstanding problems in the area of ship motions which concerned DNC. However, the terms of my post did not include the experimental research needed to pursue such ideas. Essential to the scheme I had in mind were the use of Tucker's 'Shipborne Wave Recorder' (SBWR), described in Chapter 16, and Barber's spectral analyser, together with a host of statistical techniques for wave-like motions, explored notably by Michael Longuet-Higgins.

In 1953, I contrived to visit Group W at Teddington and to join a short sea trip off Plymouth to see the SBWR in operation. Deacon and Tucker were most welcoming and I immediately felt an affinity with all the researchers I saw there. Here, at last, was a sympathetic group of scientists to whose work I felt I could contribute. After negotiations between Deacon and the RNSS, I was seconded to the NIO at Wormley as from June 1954. I later learnt that Deacon had a reputation for taking on staff who did not fit into conventional slots, and making marine scientists of them. For my part, June 1954 marked a very significant turning point in my career.

Deacon suggested that my background was best suited to a study of the papers of Longuet-Higgins, who was just about to return from two years at Cambridge, with a view to assisting him in the practical application of his theories. This proved productive. I also learnt a lot about modern instrumental techniques in oceanography from Tucker. Longuet-Higgins had suggested that the SBWR should be tested by recording waves with the ship underway on a sequence of 12 evenly-spaced courses, each held for about 20 minutes. This manoeuvre became popularly known as a 'threepenny bit', from the shape of a current coin. The idea was that waves from different directions would be separated by spectral analysis on account of their different quasi-Doppler shifts. One 'threepenny bit' had recently been executed, and Deacon suggested I should apply the spectral analyser to its analogue traces. The results neatly showed a broad spectral peak of a period 8 secs from the east, modulated sinusoidally with wave direction relative to the ship, and a superposed smaller peak of a period 15 secs propagating from the south. The latter peak indicated a superposed swell from a remote source. Later, I applied the same process to records of ship motion.

A more sensitive instrument for monitoring wave directions was the NIO pitch-and-roll buoy which recorded wave height through a vertically mounted accelerometer together with the two components of wave slope; effectively the heave, pitch and roll of the free-floating buoy. Such an instrument had been suggested by Barber in the mid 1940s, but its construction was only completed in 1955, by which time a microbarograph sensor had been added to monitor air pressure at the surface of the waves. At that time practically nothing was known about the spread of directions in wind-generated waves or about their generating pressures: existing theories about wave generation were speculative and controversial. Our deployments of the pitch-and-roll buoy from *Discovery II* in 1955-56 resulted in a set of 16 records, each about 20 minutes long, of which five were selected as representative of local wind generation and relatively free from faults. Digitisation of the initial photographic traces of wave height, slope and wind pressure onto punched cards preceded our first cross-spectral analysis by digital computers, which had been put at our disposal by the nearby Royal Aircraft Establishment.

The results were the first of their kind and quite outstanding. We showed that the waves and their surface slopes had Gaussian statistical distribution, and that their spectra tended to conform at high frequency to Phillips' inverse 5th power law. We derived useful numerical expressions for the spread of wave direction generated by real winds. Air pressure at the surface was found to be largely in anti-phase with the height profile, as expected, but with a slight phase-lag accounting for the generating process. We compared the results with a recent theory of Philips for the initial stages of wave-generation and with a theory due to J.W. Miles for the later stages where instability takes over. For the waves we encountered there was evidence that the exponential growth rate postulated by Miles was dominant.

In May 1961, a four-day Conference on 'Ocean Wave Spectra' was convened by the US National Oceanographic Office and the US National Academy of Sciences at Easton, Maryland. All of Deacon's scientists engaged in wave research were invited, as well as other leaders in the field such as Hasselmann, Munk, and Pierson. Even Barber showed up from New Zealand. Deacon was invited to give a keynote address, and our wave-buoy work was presented by Longuet-Higgins to great acclaim.[1] I presented a paper of my own on a related subject.

With the help of Norman Smith of NIO, I later experimented with two other types of wave-measuring buoys, designed for improved directional resolution. The first was a 120 m line of simplified pitch-and-roll buoys, to be towed as slowly as possible by the ship. The second was the 'Cloverleaf Buoy' which estimated the three components of curvature of the wave surface as well as the two components of slope. The results of experiments at sea using these buoys were interesting, but both systems proved clumsy to handle and so presented little effective advance on the original pitch-and-roll buoy itself.[2] The pitch-and-roll buoy was subject to intermittent jerks from its towing cable, causing sporadic changes in its 'pitch' signals. The capability of the cloverleaf buoy to resolve wave directions was limited to a rather narrow band of wavelengths, but was later put to good use during ship trials by Norman Smith and John Ewing, a late recruit to the NIO staff. The technology was later taken over successfully by Japanese wave researchers.[3]

During the 1960s, oceanographers began to realise that a single research ship was insufficient for modern analysis of systems such as waves: what were needed were simultaneous measurements by a co-ordinated group of well-separated research vessels, or later, of bottom-moored instruments. Such schemes usually required international collaboration.

Walter Munk had organised a line of swell recorders along a great-circle across the Pacific Ocean from New Zealand to Alaska, and much work had been done compiling the statistics of wave spectra and correlating them with the local windfield – e.g. by Darbyshire of NIO, and by Pierson and Moskowitz of New York. Deeper understanding of wave generation required a line of recording stations spaced along the 'fetch' of the wind. First to achieve this was Klaus Hasselmann of the Max Planck Institut für Meteorologie at Hamburg. With assistance from the Deutsche Hydrographische Institut, also at Hamburg, the Netherlands Meteorological Institute (KNMI), the Westinghouse Research Laboratory at San Diego, and NIO, a 160 km line of 13 recording stations was maintained in the North Sea, west of the German island of Sylt, during July 1969. This exercise became known as The Joint North Sea Wave Project (JONSWAP). The line comprised five ships and eight bottom-mounted recorders. NIO pitch-and-roll buoys were operated by scientists on every ship. Currents were also recorded where possible.

Hasselmann's main objective was to demonstrate the importance of energy transfer within the directional energy spectrum by nonlinear resonant interaction. This rather complicated physical process is separate from the downward transfer from the wind to the sea waves, and it results in energy depletion in some zones of the directional energy spectrum and energy growth in other directions. Among other features, it accounts for the steady growth at the long-wave (low-frequency) side of the spectral peak, which is hard to explain by elementary physics. The concept of nonlinear resonant interactions had been discussed theoretically at the Easton Conference in 1961, but the rate of energy transfer involves massive integral computations and so were far from practical evaluation, or even belief in their reality by some.

Not all the wave recorders used during the JONSWAP exercise worked successfully, but the experiment as a whole can stand as the first demonstration of nonlinear interaction in sea waves and the realisation of a true source-function for the growth of a wave-spectrum in a natural wind.[4] A parameterisation of the JONSWAP spectrum into its salient characteristics of peak frequency and spread has proved to be accurate and widely applicable to the statistics of independent wave measurements. A separate objective of JONSWAP, to trace the action of bottom-friction on swell waves, proved indeterminate.

The motion of ships at sea.

Going back to 1955, Deacon was keen for me to carry out experiments on the oscillatory motions of *Discovery II* in waves, using the facilities developed at ARL and NIO. In the mid 1950s, the only tool available for testing a ship's sea-keeping qualities was by towing a reduced-scale model in periodic waves generated in a long tank. Here was an opportunity to show not only how modern wave-measuring equipment could extend such tests to full scale at sea with waves coming from any direction (i.e. not only in head seas), but also to introduce modern ideas for analysing random wave-like motions and their statistical properties. For principles of naval architecture, I obtained valuable collaboration with Assistant Professor Louis Rydill at the Royal Naval College which was then at Greenwich.

After I had completed further measurements at sea based on 'threepenny bit' manoeuvres, Rydill and I worked up a paper on the pitching and rolling of a ship at sea which we presented to the Royal Institution of Naval Architects in 1957.[5] A second paper, concentrating on the vertical oscillations alone, was presented by me in 1958 at a Symposium at Wageningen in the Netherlands.[6]

These papers attracted the attention of Dr F.H. Todd, Superintendent of the Ship Division of the NPL, who wished to organise new approaches to ship research in the UK. The outcome of Dr Todd's initiative was an agreement for a new programme of sea-keeping experiments by NIO, NPL and the British Shipbuilding Research Association (BSRA). The first ship tested was a 'Weather Ship' (a converted naval corvette) which occupied a station 'Juliet' west of Biscay in 1959, by arrangement with the Meteorological Office.[7] Tests on other ships of more commercial importance approved by BSRA, followed in the early 1960s. Deacon was pleased to see NIO playing a useful advisory role in the national world of engineering.

Sea level, tides and storm-surges

From the mid 1950s, a research programme of national importance was engendered by the severe sea floods in winter 1953 along the coasts of the southern North Sea including London and the Thames estuary which killed about 300 people in the UK and nearly 2,000 in the Netherlands. In Britain, the principal research organisation involved in such work was the long-established University of Liverpool Tidal Institute (ULTI), and a steering committee was set up by the Ministry of Agriculture, chaired by Joseph Proudman, who had also been the founder of ULTI. The Meteorological Office, NIO, and the Ordnance Survey sent representatives and participated in the work.

Flooding at Sea Palling, Norfolk during the North Sea storm surge in January 1953. Copyright Archant Norfolk

Although NIO eventually took part in many aspects of the work promoted by the 'Flood Committee', as it was usually called, its early role was merely to examine the external surge emanating from the Atlantic Ocean. To this end, Jim Crease set up new tide-gauge installations in the Outer Hebrides and Shetland, and he constructed a mathematical model of a Kelvin Wave diffracted round a land barrier into a semi-enclosed sea.

In 1959, Dr Deacon invited a Japanese electronic engineer, Dr S. Ishiguro, to work on the response of shallow seas to air pressure and wind-stress by using networks of electrical analogue circuits to simulate the generation of a storm surge, then quite a novel approach. Suzhen (we called him Shichan, the diminutive used by his family) Ishiguro came to us from the Nagasaki Marine Observatory on a UNESCO fellowship in 1956 and, after a short return visit to Japan, Deacon offered him a job at NIO on the permanent staff.

In the electronic analogue model of the North Sea the inertia of the water was represented by inductors, the storage capacity of the surface area by capacitors, the bottom friction by resistors, and the Coriolis force due to the rotation of the Earth by rather more complicated circuits. The North Sea was divided into a grid, and each grid cell contained these components plus arrangements for feeding in the wind stress and atmospheric pressure. The grids were, of course, interconnected, and the water depth in each had to be taken into account.[8] The best summary of Ishiguro's achievements is contained in a general survey he wrote of analogue methods in oceanography.[9] But he also could take pride in his son, Kazuo, who became one of Britain's top novelists, winning both the Whitbread and the Booker prizes.

The North Sea was obviously of most interest to the Flood Committee and it became the focus of most of Ishiguro's research. He developed a series of North Sea models over many years with successive refinements as new electronic components became available, but their use as a practical working tool was eventually overtaken by digital models developed by Norman Heaps and Roger Flather at the University of Liverpool Tidal Institute (ULTI).

As a side-issue from North Sea modelling, Crease responded to a need of the Ordnance Survey for geodetic levelling between England and France by comparing the mean sea-levels measured by tide gauges along the Channel coasts, with a correction for the transverse slope caused by the action of the Coriolis stress on the mean current along the Channel. This correction could be estimated by the difference of electrical potential along an underwater telephone cable, of which NIO had first-hand experience through the work of Longuet-Higgins and Bowden. Crease and I later applied the levelling exercise to two years of simultaneous tide gauge data at Ramsgate and Dunkerque with the help of British and French authorities.[10] We found that the slope correction was 79 mm up towards France. The geodetic datum at Dunkerque turned out to be 196 mm higher than the Ordnance datum at Ramsgate. The difference in datums was eventually confirmed by the Ordnance Survey by direct geodetic levelling through the Channel Tunnel.

Tide predictions by computer

Working with tidal data inevitably introduced us to the traditional lore of tide prediction, for which ULTI was the national authority. Until about 1960, ULTI was committed to the use of an elaborate mechanical device for its tide predictions. We found it more convenient to produce our own predictions by digital computer, then still a novelty for many scientists in the UK, especially in the field of tides. In 1963-65, I was invited to work with Munk at Scripps who was developing a modern approach to the analysis of tides, made possible by the large electronic computers available in the USA. The analytical scheme which Munk and I worked up was based on the physical response of the ocean to the lunar and solar tidal forces, and became known as the *Response Method* as distinct from the traditional *Harmonic Method* with its roots

David Cartwright inspecting output from the IBM 1800 computer at Wormley.

in the late 19th century. Tide predictions by the *Response Method* were demonstrably more accurate. Our paper[11] was acclaimed as a 'landmark' in the literature on tides, though in practice use of the *Response Method* was limited to a few experts.

When a member of his staff wanted to pursue a promising idea in marine science, Deacon tended to adopt a *laissez-faire* policy. On my return to NIO after 17 months in California, Deacon allowed me a free hand to apply my newly acquired knowledge to the aims of the national Flood Committee. NIO had yet to acquire its own mainframe computer, but an arrangement was made for NIO staff to use the (then) 'large' computer at IBM in London. On one occasion, Longuet-Higgins had consumed such a heavy load of computer-time in computing a series of eigen-functions that IBM allowed us 5-6 hours of computer time without charge. For my part, I was able to construct a forecasting system for hourly sea levels around the British North Sea coast, using a *Response Method* not only for the tides but also for the surge-response to pressure and wind and their dynamic nonlinear interactions between tide and surge.[12]

Recording offshore tides

Another export from Munk welcomed by Deacon was a project to develop instrumentation for recording the tide in the open sea through changes in pressure at the seabed. The idea was not new, but very high precision was required to record changes of a few millibars against the ambient pressure of at least a few hundred to a few thousand bars. The instrumental technology was only just becoming possible for such high precision. There was then a dearth of knowledge about the tides offshore which, if well known, would have important applications to geophysics and lunar theory as well as offshore engineering technology. Attempts by mathematicians since Newton's time to solve the dynamic equations of the global tides had failed: existing measurements at harbour tide gauges were too distorted by coastal topography to be extrapolated far offshore. Once the technology had been established, Munk envisaged a network of oceanic tidal pressure measurements which could be used as the basis for digital models. In this he had the backing of UNESCO's Scientific Committee on Oceanic Research (SCOR) which was willing to provide money to aid workshops and travel. In 1965, only the US and France had realistic plans to participate in such a scheme. We at NIO were able to join them shortly on behalf of the UK.

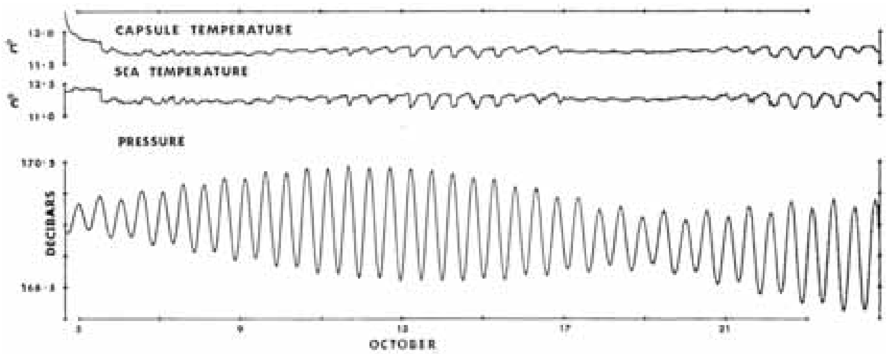
Central to the overall problems was the global rate of dissipation of tidal energy, then (in the 1970s) thought to be in the region of 2 Terawatts (a Terawatt is a million, million watts) for the lunar half-daily tide alone. 2 TW is quite a small quantity compared with the amount of energy already raised in the ocean tides, but quantification was vital to the understanding of, for example, the steady increase in the length of the day, the rate of recession of the moon from the earth, and, as it later turned out, the capacity of the ocean circulation to overturn.

Short of a mathematical solution, a solution for the mean rate of dissipation could in principle be obtained by estimating the rate of working of the (known) tidal stresses on the ocean, and its divergence (method 1), but this would require measurement of pressure variation at every point of the earth's surface. Alternatively (method 2) one could divide the area into finite seas with tidal measurements along every boundary, including tidal currents. The currents are in principle depth-averaged, so more difficult to estimate. Method 2 was thought to be more feasible at the start of the SCOR-funded campaign, on the assumption that all dissipation occurs in shallow seas due to bottom friction. That assumption was called into question as dissipation by internal tides in the deep ocean became quantifiable, and indeed internal tides are now known to constitute a non-negligible sink of energy.

For this campaign, NIO had a 'laboratory' at hand in the complex of shelf seas surrounding Britain and Ireland, mostly washed by large tides. As later technology developed, we also extended external boundaries across the deep ocean, from Portugal to Canada, from Iceland to the Azores, and between West Africa and North Brazil.

NIO scientists were familiar with the principles of pressure recording from their work on waves, but there was a long way to go before reliable and accurate – tenth of a millibar – records could be made in even 200 m depth. Temperature sensitivity was a bugbear because temperature also varies tidally, and ability to record for at least a month before recovery of the instrument was another challenge. Acoustic release systems were still in their infancy. It was necessary to record continuously for at least a month in a depth of at least 150 m, ideally in 2,000 m or more, with precision better than one part per million. Tucker, then head of the Applied Physics Group, provided the initial lead with capacitance-plate pressure sensors and digital recording. The techniques were developed by Peter Collar and Robert Spencer, who eventually exceeded the desired goals by the use of refined technology. Collar's and Spencer's first experimental deployment in 1969 in the Hurd Deep west of Guernsey recorded for 14 days at 104 m depth and proved the technology to be viable; by 1971 the team was getting excellent month-long records at the shelf-edge in 188 m.[13]

Our first plan was to record tidal variations of pressure along the shelf-edge surrounding Britain and Ireland between Norway and Brittany at intervals of about 50 sea miles, with the object of providing tidal boundary conditions for a relatively large expanse of shelf-seas bounding the northeast Atlantic. Where feasible, the pressure data were supplemented



One of the early offshore tide records from La Chappelle Bank in October 1969. Note the 14 day springs-neaps cycle and also the downward drift in the average pressure due to sensor drift.[13] *(1 decibar is approximately 1 metre.)*

by currents. In the region south of the island of St. Kilda these revealed an area of enhanced diurnal (changing once per day) currents, not obvious from the pressures alone. A similar effect had been noted for centuries by fishermen in the Sound of Harris (Outer Hebrides), but never satisfactorily explained. Our measurements showed for the first time that the diurnal currents were spread over a relatively wide area of shelf and could be explained by a form of resonance known as shelf waves associated with the local bathymetry including the deep ocean.

The programme together with careful analysis by the *Response Method* took until about 1978 to complete, by which time our technicians had extended the depth capability to 3,000 m with the use of Digiquartz sensors. However, this takes us into the era of the IOS.

An international calibration exercise

The last event in the NIO tidal programme before its transfer to IOS at Bidston, near Liverpool, was a calibration exercise for pressure recorders deployed from *Discovery* towards the end of 1973. All active members of the SCOR Working Group 27 on 'Tides of the Open Sea' were invited to compare their pressure recording techniques for a month at two sites near the shelf-edge west of Brittany. One of the recording sites was fairly deep at about 2,000 m; the other was a 'shallow' site at about 200 m, both in reasonably flat bathymetry. Thus, both types of technology, shallow and deep, were catered for. Participants included the US, Canada, France and the UK. The UK was the only team to feature instruments for both shallow and deep technology. There were a few unfortunate losses of equipment at both sites, but the instruments recovered showed remarkable agreement in tidal amplitude and phase, and were therefore worthy of continuing the programme.[14]

Forward look – the impact of space geodesy

On a clear evening in October 1957, many staff of NIO, including Deacon, assembled on the flat roof of the NIO building to witness a passage of the first Russian satellite, *Sputnik 1*. Though vastly impressive, it was not immediately apparent how the new technology could benefit oceanography. But in the ensuing years infrared and microwave sensors mounted on satellites slowly became accepted as useful tools for monitoring the ocean, opening up radically new approaches to the subject. The study of ocean tides, as well as much dynamical oceanography, was transformed when satellite radar altimeters backed up by high precision space geodesy began to monitor heights of most of the ocean surface to precisions of at first a few decimetres, then steadily refining to as little as a few millimetres by the 1990s. Some physical oceanographers (including myself) started to follow developments from the later years of NIO onwards, and we played a palpable role in the choice of suitable orbits at meetings of the steering committees of NASA and of the European Space Agency. The success stories of the US/French TOPEX-Poseidon and the European ERS satellites and their sequels owe a lot to research into ocean tides which started in the sea-going efforts of SCOR's tidal Working Group, as well as other disciplines in physical oceanography.[15]