**The Shipborne Wave Recorder**

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## Background[1]

Measuring the height and period of waves on or from a ship at sea has been tackled in a number of ways. In the mid 1870s officers on the German research vessel *Gazelle* attempted to use a very sensitive barometer to measure air pressure fluctuations caused by waves and the motion of the ship, with little success. Later, the advent of seaplanes, with the consequent need for knowing wave conditions in the open sea, was one reason for the development of wave measurements from ships. One successful method, developed in Germany in the 1930s, involved deploying a surface float with a weighted pressure recorder beneath at the end of a 30-60 metre tether. In a British version, the pressure measurements were transmitted by radio from the buoy to the attending ship. However, this method, and others that required apparatus to be deployed from the ship, was attendant with the practical difficulties of handling equipment overboard in bad weather.

How could waves be measured from within the ship? A solution to this problem that began in the late 1940s, and was to prove effective for five decades, is forever associated with "Tom" Tucker who spent most of his career with the National Institute of Oceanography at Wormley. M.J ("Tom") Tucker had joined Group W at the Admiralty Research Laboratory in Teddington in December 1944. A 19-year old graduate physicist, he soon began to specialise in electronic engineering. His early work included maintaining wave recorders that used pressure sensors deployed on the seabed off Cornwall connected to shore by cables. Much of Tucker's work at Teddington involved mechanical as well as electronic components (nowadays termed "mechatronics"), and he began a "happy and fruitful" collaboration with Frank Pierce, a mechanical engineer, who was also to go on and join the staff at Wormley. One product of their collaboration was the Shipborne Wave Recorder.

## Design and development of the Shipborne Wave Recorder

Tom Tucker's concept for a Shipborne Wave Recorder (SBWR) was for an instrument "contained completely within the hull of a ship" that made two measurements, the height of the water surface above a known point, and the height of that known point from an arbitrary fixed reference point. Combining the two measurements gives the height of the water surface above the fixed reference point, hence the wave height, irrespective of the movement of the ship.

A pressure sensor, inside the hull of the ship, well below the waterline, exposed to the sea through a small port, would measure the height of the water surface. For reasons well explained by Tucker in detailed reports and papers[2] errors in this estimate of water height, for example due to waves arriving from one side of the ship, could be reduced by taking the mean height from two pressure sensors, fitted exactly opposite each other on the port and starboard sides of the hull. This simplified drawing of Frank Pierce's mechanical design for the pressure measurement unit shows the components involved. An inlet valve could be shut off to isolate the unit from the sea outside the hull, for example for maintenance. Rather than allow the corrosive seawater to make contact with the precision pressure sensor, the water pressure acts on a rubber diaphragm at one end of an oil-filled chamber, which houses an air-filled metal bellows. The movement of the bellows was converted to an electrical signal by a novel linear displacement transducer of Tucker's design.

The second measurement, that of height of the known point from an arbitrary fixed reference point, was more of a problem. While acceleration could be measured by an accelerometer, ensuring that the acceleration in the true vertical plane was being measured proved a challenge. Pitch and roll motion of the ship would offset the measurement plane of a static accelerometer from the vertical, and an accelerometer on a pendulum or gimbal would be affected by sideways accelerations due to the waves. The ideal solution, an accelerometer on a gyroscope, was not affordable. Tom Tucker's solution, turned into a practical device by Frank Pierce and colleagues, was to accept the limitations of a gimballed accelerometer, after showing that the error would manifest itself as a long slow fluctuation that could be mostly eliminated by the electronic circuitry that

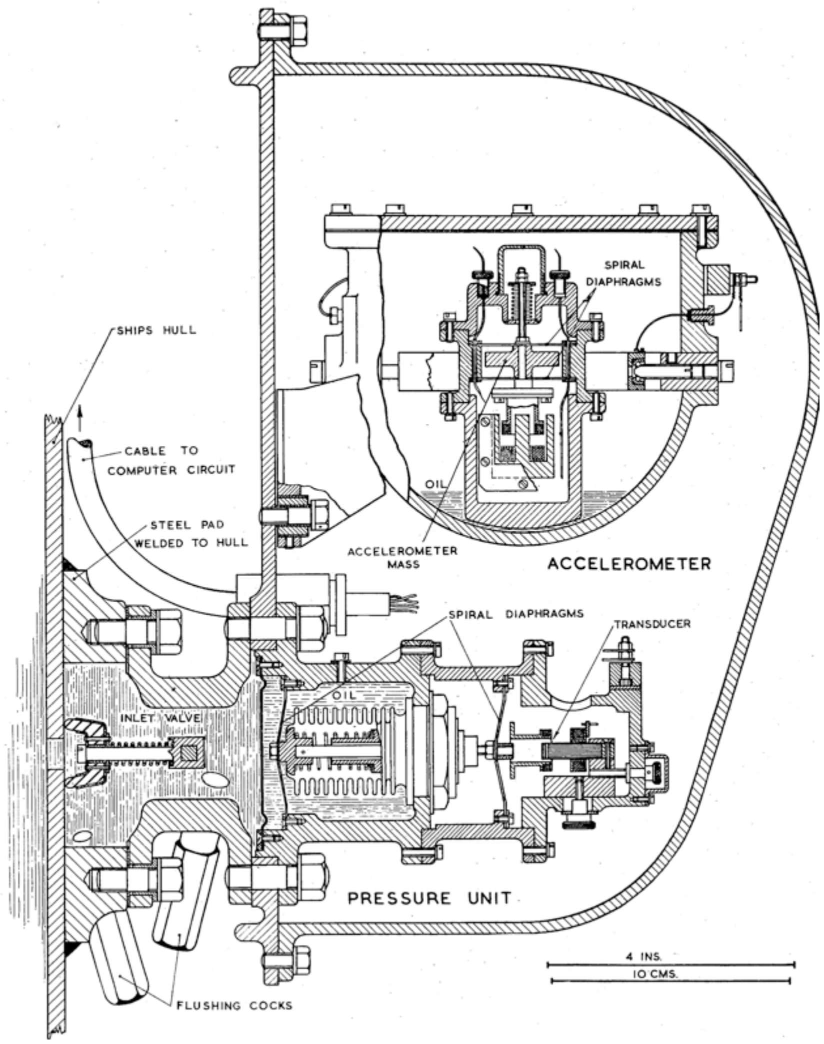
[1] Part of this introductory material comes from

Tucker, M.J., 1952. A wave-recorder for use in ships. *Nature*, 170: 657-659

and from Tucker's own contribution to

Laughton et al., *Of Seas and Ships and Scientists*, 2010. Lutterworth Press, pages 55-58

[2] For example, Tucker, M.J., 1956. A shipborne wave recorder. Transactions of the Institution of Naval Architects, 90: 236-250.




performed the double integration of acceleration, first to velocity, and second to displacement in a manner that was "only just good enough for the job in hand"[3] .
The pressure sensors and accelerometer were energized by a 1000Hz AC oscillator comprising five electronic valves. Tucker employed a recently-introduced circuit technique to keep the oscillator's output constant, to avoid drift in the measured wave output, and he used modern components, the final amplifier valves[4] had only been introduced two years before the instrument was first used at sea.
The final part of the recorder was what Tucker called the "Electronic Computer Circuit". Comprising seven valves, the circuit rectified the signals from the transducers, performed the double integration of the accelerometer signals, effectively added the pressure and displacement signals and provided a voltage output that could be recorded on a paper strip chart.

**Deploying, maintaining, and developing the SBWR**

This section deals with the practical implementation of Tom Tucker's original design, calibration techniques, installation considerations and the development of the instrument over the period 1951 to 1995.
Initially valve circuitry was the only option, this worked perfectly well but brought with it penalties in terms of weight and size of the control unit which included the paper chart recorder. The latter worked on the principle of a large and sensitive galvanometer, one consequence of which was heavy magnets. In addition, the power consumption and relatively high voltage of the valve-based system involved a substantial transformer and other bulky components.
The transducers would be in the engine room or a compartment where holes could be drilled at points below the water line as shallow as possible but consistent with the requirement that they rarely became exposed to air when the vessel rolled. A brass assembly would be bolted to the inside of the hole pads which incorporated a water valve to isolate the pressure transducer for maintenance purposes, and a mounting frame for the bowls that contained the gimballed accelerometers.
The positioning of the whole transducer assembly was critical: the optimum depth is mentioned above but it was also essential to try and find a position of minimum pitch which, of course, would usually be around the centre point between bow and stern. Quite often it was very difficult to meet these requirements so an expert

One of the SBWR transducer assemblies bolted to the hull of the Norwegian weather ship *Polar Front*. The electronics interface card sits atop the brass bowl housing the gimballed accelerometers. The shut-off valve is seen within the bight of the grey cable.

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[3]Trans INA, 1956
[4] See http://www.r-type.org/exhib/aai0031.htm

survey of the ship was a necessity before installation. The method of power and signal transmission (using an amplitude modulated precision sine wave) between the control unit and sensors meant that length of cable was not usually an issue.

The control unit would normally be situated adjacent to, or in the region of, the bridge of a ship where ready access existed for changing pens, ink and charts, and observing the wave trace.

A special 'portable' calibrator unit was designed and manufactured. It comprised a mercury column manometer against which the pressure units could be calibrated using a hand pump to generate a range of static pressures and a 'swinging arm' or rotating rig which enabled the accelerometer to be moved around a 1 metre diameter circle which would result, after precise amplification, in a sinusoidal trace on the paper chart. Clearly this apparatus could only be used on land or on board a moored vessel where there was virtually no motion i.e. in a well-protected harbour.

Typically, deployment of the SBWR would be for several years with an annual calibration, although in the case of lightships it would be for three years – the interval between refits. A useful check on correct functioning between calibrations involved a monthly test routine comprising the running of four ten minute records, one for each individual sensor. The records from each accelerometer should be very similar since, in open-ocean, very little change in wave characteristics would occur over 20 minutes. A comparison of individual pressure unit outputs, however, might show more variability since wind and waves could be more prevalent on one side of the hull but this would even out over several monthly samples. Accordingly, these regular tests carried out by the crew were a good indicator of instrument behaviour.

Metocean and navigation instruments on the Norwegian weather ship *Polar Front*. The SBWR console is in the centre rack.

It was recognised in the early 1970s that reliability of transistorised circuitry meant that it was practical, and sensible, to re-design the control unit. This was done using the same amplitude modulated transmission system and the same sensor assemblies. Thus was born the Mk II SBWR. However, the sensor assemblies were difficult and expensive to produce and the next stage became to replace these with solid-state devices such as a forced feedback accelerometer and a strain gauge pressure unit. At the same time it was decided to change the signal transmission system to the 4-20 mA principle giving improved protection against electronic interference. This also simplified the control unit since it was no longer necessary to provide a reference oscillator. This then could be described as the Mk III.

The calibration process was also made more manageable since a high accuracy solid-state pressure reference could be used instead of the manometer although the principle of the swinging arm was retained, but somewhat simplified, by using a stepping motor.

Finally, a major update of the control unit recognised that the problems of data collection and analysis using chart recorders could be solved by incorporating a digital output. This represented the final stage of development for the SBWR.

**Engineering and scientific uses of the SBWR**

The main engineering uses of wave statistics from the SBWR have been in estimating wave climate and extreme values. Methods for estimating long term wave statistics around the UK were described in Tucker and Pitt (2001). UK waters have been monitored for many years with the SBWR; for example over 16 years of measurements have been obtained from the Seven Stones light vessel off Land's End (Bacon and Carter, 1989). A comprehensive review of wave measurements around the UK, including the SBWR, has been given by Draper (1991). These SBWR measurements played a significnt role in quantifying the long-term changes in wave climate; see for example Bacon and Carter ( In recent years the SBWR has been replaced by remotely recording data buoys.

A major advance in our understanding of ocean waves was made by Moskowitz. He selected 54 records out of over 400 recordings from weather ships in the North Atlantic corresponding to fully-developed seas. These records were then digitized and analysed by Pierson and Moskowitz (1964) to obtain the spectrum of fully-developed seas based on similarity arguments used by S.A. Kitaigorodskii. The high frequencies (short wavelength) end of the wave spectrum was fitted with a “Phillips” tail as this region could not be measured with the SBWR.

Early studies of ship motion greatly benefitted from the use of the SBWR. Simultaneous measurements of waves and ship motion were carried out by a consortium of the Admiralty Experiment Works, British Ship Research Association, National Institute of Oceanography and the National Physical Laboratory on ocean weather ship “Weather Reporter” (Canham et al. 1962). Subsequent ship trials used the NIO pitch-roll buoy to provide estimates of the directional wave spectrum which was important since the SBWR was not able to provide information on wave direction.

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February 2016