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Great ships, solitary waves, and solitons

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John Mellis has spent most of his career as a physicist, engineer and project manager working on optical telecommunication systems at the BT Research Laboratories in Suffolk. For many years he was also a Visiting Professor at the University of Sunderland. He now writes on the history of science, technology and medicine, and is the author of Scotland's Science (1550-1900) and Scotland's Science Next (1850-2022). He is a member of the British Society for the History of Science, and is a Fellow of both the Institution of Engineering and Technology, and the Institution of Engineers in Scotland.

Abstract

John Scott Russell was one of the foremost naval architects of his time. Born near Glasgow in 1808, he became a noted and popular lecturer, before moving away from academia to focus on industrial engineering. Among his many achievements, two stand out. First, the design and construction of the SS Great Eastern in collaboration with Isambard Kingdom Brunel. Second, the discovery and study of a strange wave phenomenon he acutely observed on the Union Canal near Edinburgh. Scott Russell's 'Wave of Translation', now known as Solitary Waves or solitons, turned out to have significance and application in many fields, including optical telecommunications.

John Mellis

In 1851, the Australian Royal Mail Steam Company wanted ships that would make the journey from Britain to the Antipodes taking on coal only once, at the Cape of Good Hope. They turned to their chief engineer, the great ship designer of the age, Isambard Kingdom Brunel, creator of the largest ship afloat, the *SS Great Britain*, which measured 322 feet long, and displaced 3,675 tons[1]. In response, Brunel produced a specification for ships displacing between 5,000 and 6,000 tons. The company baulked at what they saw as the over-ambitious design. So instead, Brunel commissioned another design for two smaller ships from the well-known Scottish naval architect, John Scott Russell, which would still be able to carry enough coal to meet the requirement. Russell owned the respected and reliable Fairbairn ship-building yard at Millwall. Under the contract, two large iron-hulled mail steamers, the *Victoria* and the *Adelaide*, each carrying 200 passengers, were designed, constructed and launched successfully[2] (Brown, 2004). The *Victoria* won a prize for the fastest passage to Australia: 60 days, including a two-day stay at St. Vincent. By the spring of 1852, Brunel was wondering how to design a ship capable of sailing to the Far East, and back again, carrying all its own fuel. He began discussing plans with Russell for a truly enormous ship, over 600 feet long, and displacing more than 21,000 tons. It would become the *SS Great Eastern*.

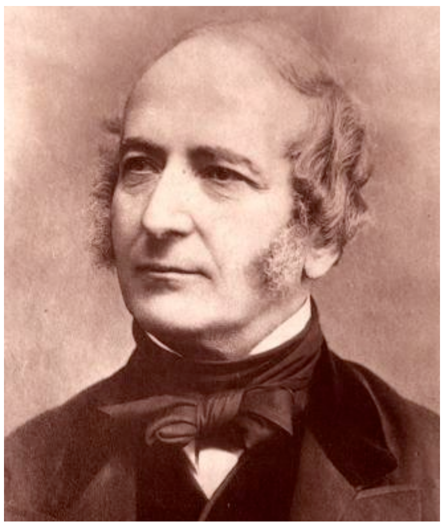

Figure 1. John Scott Russell, engineer and naval architect

1 Brindle S (2006) Brunel: the Man who Built the World, Weidenfeld & Nicolson

2 Brown D K (2004), Russell, John Scott (1808-1882) Oxford Dictionary of National Biography https://doi.org/10.1093/ref:odnb/24328

John Scott Russell was a naval architect and engineer. Among his many achievements, two stand out: first, the construction of the *SS Great Eastern* in collaboration with Brunel; second, the discovery of a strange wave phenomenon which has had many profound implications in the modern fields of fluid dynamics and optical telecommunications. Scott Russell was born the only son of a clergyman, Rev. David Russell, and Agnes Scott in Parkhead, now a part of Glasgow but then a local village. At the age of 12, he studied for a year at the University of St Andrews before enrolling at Glasgow University to study mathematics and natural philosophy, graduating when he was only 17 years old[3]. Encouraged by his old professor of geometry at St Andrews, he taught mathematics and science at the Leith Mechanics Institute, and at Edinburgh University, where his lectures were highly popular and so well-attended that *"when he commenced his second course of lectures, the classrooms of his former master and actual rival were rapidly emptied."* On the vacancy of the chair of natural philosophy at Edinburgh, due to the death of Sir John Leslie in 1832, Scott Russell (then aged 24) was temporarily elected to the post, pending the appointment of a permanent new professor. He was encouraged and invited to apply, but declined to compete with another candidate he greatly admired, the optical scientist David Brewster, who ironically did not get the job but later became Principal of St Andrews University. Scott Russell was in any case more interested in industrial applications, and moved away from academia. He briefly ran the *Scottish Steam Carriage Company*, which offered steam-car passenger transport between George Square in Glasgow and the Tontine Hotel in Paisley, until a fatal accident ended the service[4] It was while consulting for a company operating a passenger steam-boat service on the Edinburgh and Glasgow Union Canal, that John Scott Russell discovered a most amazing phenomenon.

In 1834, he was conducting experiments at the Union Canal near Hermiston to determine the most efficient design for canal boats, observing a boat being towed along rapidly by horses. When the boat stopped, the bow wave continued forward in a very unusual way. He described his discovery like this: *"I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped—not so the mass of water in the channel which it had put in motion; it accumulated round the prow of the vessel in a state of violent agitation, then suddenly leaving it behind, rolled forward with great velocity, assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height. Its height gradually diminished, and after a chase of one or two miles I lost it in the windings of the channel. Such, in the month of August 1834, was my first chance interview with that singular and beautiful phenomenon which I have called the Wave of Translation, a name which it now generally bears..."*[5] .

Scott Russell knew that in his 'Wave of Translation', which he also called 'solitary waves', he had observed something fundamentally important. He built an experimental tank in his garden to continue his studies of it, developing his observations of the strange solitary waves and measuring their key properties: stability and resistance to dispersion, so that they can travel over great distances; their high speed; and the dependence of speed on the width and depth of the water channel[6]. The wider relevance of Russell's solitary waves only became clear in the 1960s when scientists began to use digital computers to study non-linear wave propagation in fluids and in solid materials. It became obvious that many phenomena in physics, electronics and biology can be described by the theory of 'Russell's Solitary Waves' as they are now known in fluid dynamics, and of 'solitons' as they are called in the field of fibre-optics.

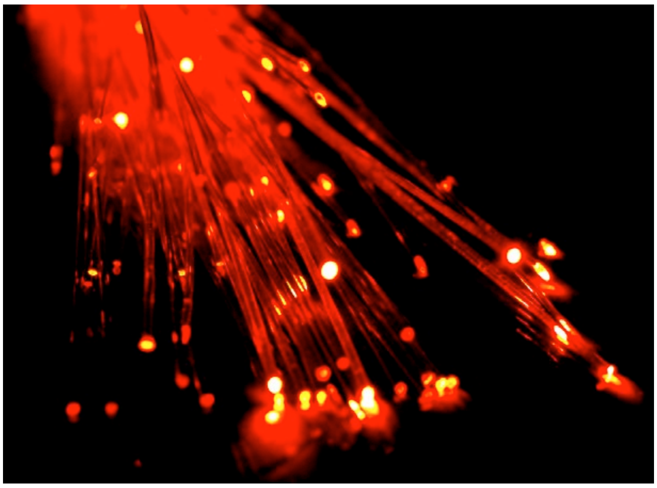

Figure 2. A bundle of optical fibres

3 Brown D K (2012), Russell, John Scott (1808-1882) Oxford Dictionary of National Biography https://doi.org/10.1093/ref:odnb/24328

4 Petroski H (1998) John Scott Russell, American Scientist, Vol. 86, pp 18-21. https://www.jstor.org/stable/27856932

5 Russell J S (1884) Report on Waves, Report of the Fourteenth Meeting of the British Association for the Advancement of Science, York, pp 311-390 https://www.biodiversitylibrary.org/item/47344
Eilbeck, C (2013) John Scott Russell and the solitary wave, Heriot-Watt University, Dept. of Mathematics http://www.macs.hw.ac.uk/~chris/scott_russell.html

6 Russell J S (1885) The Wave of Translation in the Oceans of Water, Air and Ether, pub. Trübner & Co. https://archive.org/details/wavetranslation01russgoog

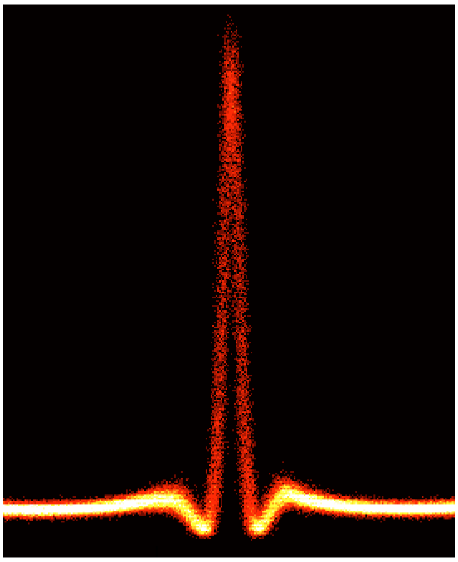

Figure 3. Temporal profile of a soliton at the point of maximal compression. K. Hammani et al. (2011)

Solitons especially caused great excitement in the fibre-optic communications industry. The qualities of solitary waves which intrigued Russell – the fact that they do not fragment, disperse, or lose strength over distance – prompted Akira Hasegawa at AT&T Bell Labs to propose in 1973 that solitons could exist in optical fibres if a sufficiently powerful light pulse exploited the non-linearity of an optical fibre's refractive index properties in exactly the right way to balance the dispersion of the pulse. Laboratory experiments confirmed that solitons could be used for ultra-high-speed communications where billions of solitons per second carry information down immensely long optical fibre links. For example, in 1999 the NTT laboratories in Japan demonstrated transmission of solitons at 10 Gigabits per second over a fibre-optic length of 180 million kilometres, and at 80 Gigabits per second over 10,000 kilometres (Nakazawa, 2002). Recirculating solitons in tiny optical 'microresonators' have been used to generate a 'comb' of frequencies to incredibly high precision. Such frequency combs can be used to generate closely-spaced optical carriers with an immense combined data capacity – researchers have used 179 optical carrier frequencies to transmit 55 Terabits of data per second over a distance of 75 km – the equivalent of two million HD TV channels[7]. Optical frequency comb generation has become an important scientific tool, one that enabled the measurement of the spectral line wavelengths of hydrogen to an unprecedented precision of 1.4 parts in 10^{14} – for which Theodore Hänsch and John Hall shared the 2005 Nobel Prize in Physics[8]. John Scott Russell's acute observation of his 'heap of water' has had implications that have rippled far and wide indeed.

Back in the 19th century, Russell's immediate concern was in understanding how his wave of translation could be used to optimise the design of ships. He reported his original observation in a paper presented in 1835 to the Bristol meeting of the British Association for the Advancement of Science, and showed how the wave of translation could be used to reduce the water resistance to vessels moving fast in a restricted waterway. The interest was so great that Russell and Sir John Robinson, secretary to the Royal Society of Edinburgh, were appointed to carry on the investigations into the whole subject of waves, at the Association's expense. They reported back after two years, with three wide-ranging papers, including: *'On the Mechanism of Waves in Relation to the Improvement of Steam Navigation'*, in which Russell described a new approach to optimising the design of ship hulls, which he called his 'wave-line' theory. In essence, this proposed that the profile of ship hulls should resemble the shape of the bow waves they created, with slim, concave bows shaped as sinusoidal curves to push water aside with minimum energy. This was a semi-empirical deduction, rather than a mathematically rigorous one, but it had a strong influence on subsequent hull design, as in the fast 'clipper ships' of the 1840s and beyond. Finding an entire hull shape to minimise water resistance was a problem that would be solved by William John Macquorn Rankine and William Froude many years later. Working at the Greenock shipyard of Thomson and Speirs, Russell introduced his wave-line designs to a series of vessels, including the *Skiff, Wave, Storm* and *Scott Russell*, followed by four fast Royal Mail ships, the *Teviot, Tay, Clyde* and *Tweed*. As well as their innovative, streamlined hulls, Russell introduced new structural designs for the iron ships, involving a system of longitudinal girders combined with numerous transverse bulkheads and a continuous iron deck; in effect, a box-girder construction conferring great strength and stiffness to the ships.

In 1836 Russell married Harriette Osborne, the daughter of Daniel Toler Osborne, an Irish baronet, and in the course of the next few years they had two sons and three daughters. His reputation as a foremost naval architect was established, and in 1844 Russell relocated his family to London, where he became engaged in a range of writing, editorial and engineering projects. He was invited by the

7 *Landgraf, M (2017) Optical communication at record-high speed via soliton frequency combs generated in optical microresonators, at Phys.org https://phys.org/news/2017-06-optical-record-high-soliton-frequency-microresonators.html*

8 *Hänsch, T (2005) Passion for Precision, Nobel Lecture (2005) https://www.nobelprize.org/uploads/2018/06/hansch-lecture.pdf*

Society of Arts to be its joint secretary, and helped to initiate its proposals for a Great Exhibition in what would become the marvellous Crystal Palace. In the aftermath of the Exhibition's great success, the dismantling of the Crystal Palace, and its reconstruction at Sydenham, in the south of London, the Prince Consort, Prince Albert, wrote that many difficulties had been encountered, and it was *"by dint of Mr. Scott Russell's tact, judgment, penetration, resource and courage, that obstacles vanished and intrigues were unmasked."*

Throughout his life Russell's main preoccupation remained firmly in naval architecture and shipbuilding, and in 1847, with partners, he acquired the Fairbairn shipyard at Millwall, and constructed the wave-line based yacht *Titania* for the English railway engineer Robert Stephenson, and *Adelaide* and *Victoria* for Isambard Kingdom Brunel and the Australian Royal Mail Steam Company. Titania enabled Stephenson to join the Royal Yacht Squadron, which had invited the New York Yacht Club's own wave-line based *America* to compete at Cowes for their Hundred Guinea Cup. In August 1851 *America* resoundingly defeated a flotilla of 14 British boats in the race that became the America's Cup. In the 'London Journal' a cartoon showed Queen Victoria asking which yacht came second, and being told *"Ah, your Majesty, there is no second."* A week later *America* raced *Titania* head-to-head in a battle of wave-line designs and won again. Russell acknowledged the victory graciously.

Meanwhile, ever ambitious, Brunel was hatching plans for his most audacious project yet. In 1852 he began sketching designs and calculations for an enormous ship capable of carrying its own fuel for an uninterrupted round trip from Britain to the Far East. In the finalised design the ship would measure 692 feet in length by 83 feet in the beam, displace 27,000 tons, and carry 4,000 passengers, 3,000 tons of cargo and over 10,000 tons of coal. To finance the project Brunel approached the Eastern Steam Navigation Company (ESNC) which had just competed unsuccessfully to win mail contracts to the Far East. Surprisingly, the beleaguered company accepted Brunel's bold vision and appointed him its chief engineer. To build the great ship, to be called the *Leviathan*, quickly became Brunel's major obsession and the ESNC's critical project. They invited tenders to build the ship, and received only one to build the whole ship, including engines, from Scott Russell's Millwall yard. Russell offered to build the hull for £275,200, with the paddle engines and boilers for £42,000 and the propeller screw engines and boilers for £60,000, sub-contracted to James Watt & Co. of Birmingham. This total was a great under-estimate compared to Brunel's private estimate of £500,000 to build the whole ship. The sole tender was accepted but the project soon ran into problems.

Construction started well and with high quality outcomes. The hull embodied the well-established Russell philosophy of a wave-line form, longitudinal iron stringers and strong bulkheads. But the sheer scale of the ship required Scott Russell's company to hire the neighbouring Napier yard to accommodate the work, and Brunel's frequent design changes increased the costs. By 1856, J. Scott Russell & Co. were insolvent and the ESNC took control of the yards to complete the ship, now becoming known as the *Great Eastern*. In January 1858, she was eventually launched, after many issues and a fatal accident related to her huge size and weight. The construction had cost £600,000 to that point, contriving the difficult launch had cost £120,000 and another £200,000 was required for the engines and fitting out. The ESNC was forced into liquidation with huge losses for its shareholders, including Brunel, and sold the incomplete ship for £165,000 to a newly formed 'Great Ship Company'. Scott Russell had managed to resurrect his own business and won the contract to complete the fitting out. The *Great Eastern* sailed for the first time in September 1859 and almost immediately, a stopcock left accidentally closed caused an explosion which killed five stokers. Brunel, already terminally ill, died several days later and never saw his and Russell's 'great babe' at sea.

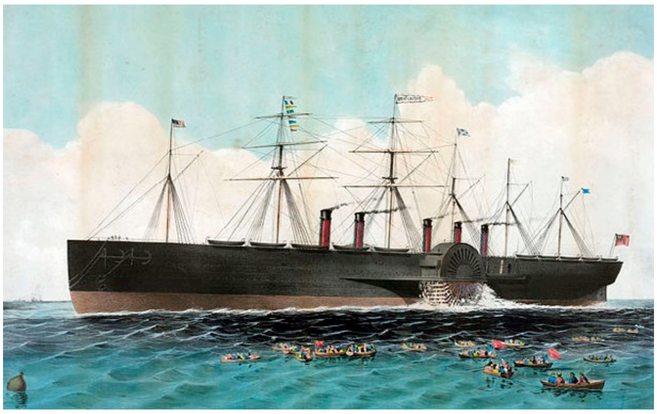

Figure 4. The S.S. Great Eastern. Hand-coloured lithograph by Charles Parsons

The *Great Eastern* was never a commercial success apart from her use in laying sub-oceanic telecommunication cables. But she was a masterpiece of pioneering design, too far ahead of her time. It would be another 49 years before a larger ship was constructed: the Clyde-built Cunard liner *Lusitania*. The first failure of Scott Russell's shipyard initiated a series of financial problems for him. Involvement in a business to supply guns to the American Civil War also left him heavily indebted and much of his property was sold. The bankruptcy of his son's shipyard on the River Taff in 1869 caused him further losses. Russell's later career was spent as a consulting engineer producing designs such as the Great Rotunda for the Vienna Exhibition of 1873, then the world's largest clear-span roof. He prepared some designs for the 1,000-foot span required for the London Tower Bridge, but while investigating potential ironworks for the project, he became ill and eventually died aged 74, in 1882.

In July 1995, an international group of scientists attended a conference on 'Nonlinear waves in physics and biology' at Heriot-Watt University, and gathered on the Union Canal near Edinburgh to witness a re-creation of Russell's famous first sighting of a solitary water wave[9]. The occasion marked the naming of the new 'John Scott Russell aqueduct' which now carries the Union Canal over the Edinburgh City Bypass.

Picture credits:

Figure 1 Wiki CommonsL https://commons.wikimedia.org/wiki/File:Russell_J_Scott.jpg

Figure 2, Tyler Nienhouse https://commons.wikimedia.org/wiki/File:Red_optical_fibers.jpg /File: Red optical fibers.jpg CC Attribution2.0 Generic licence

Figure 3, K. Hammani et al (2011) https://commons.wikimedia.org/wiki/File:Peregrine_soliton_in_optics.png

from Peregrine soliton generation and breakup in standard telecommunications fiber, Opt. Lett. 36, pp 112-114.

Figure 4, Charles Parsons , Hand-coloured lithograph of the SS Great Eastern https://commons.wikimedia.org/wiki/File:Great_Eastern_painting_smooth_sea-2.jpg, public domain

9 *Hänsch, T (2005) Passion for Precision, Nobel Lecture (2005) https://www.nobelprize.org/uploads/2018/06/hansch-lecture.pdf*