Louis Essen and Atomic Time

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To state that the world's first atomic clock was built in the home of King William IV would be a memorable opening sentence for an essay, but it would not be exactly true. And since this is an essay about accuracy, it is best to explain that the first time-piece using atomic resonance as the basis of its mechanism was built in America, although that particular machine broke no records for precision. I should also explain that William, third son of George III, was long dead before the residence he occupied as the Duke of Clarence, Bushy House, was selected to become the National Physical Laboratory of the UK. This stately mansion sits at the northern edge of Bushy Park, about half a mile north of Hampton Court Palace, the magnificent complex on the Thames, begun by Thomas Cromwell, that became one of the most famous of royal palaces. The new laboratory at Bushy House opened in 1900. In 1946, Alan Turing developed his Automatic Computing Engine (ACE) there. Packet switching, used by all internet connections, was invented at NPL by Donald Davies in the 1960s. Between these two breakthroughs came the much-celebrated work of Louis Essen and his assistant Jack Parry, who constructed the first clock more accurate than any astronomical measurement.

Louis Essen was born in 1908 near Nottingham to working-class parents. His father was a boot and shoe maker who worked long hours for a poor living. Essen won a scholarship to the local grammar school, and did very well there with the particular encouragement of one of the masters. He went on to attend University College Nottingham (because it was close to home) to study physics, and was the only student of his year to obtain a first-class degree. During this time he became an expert in glassblowing, as much of his work was on the properties of gases. He also became proficient in scientific German, and helped his supervisor Henry Brose to translate papers by Einstein among others that were not available in English. The economic situation of the country was poor, so rather than study for a doctorate, Essen took a job at NPL straight after graduating. He stayed there for the entire 43 years of his working life.

Essen's first position was working under David Dye, who had invented a quartz oscillator in the shape of an annular ring. The frequencies of radio transmitters were rather poorly controlled in the late 1920s, and Dye was looking for a new regular oscillator, so that the Post Office could broadcast a signal of fixed, known frequency for others to use as a standard. Essen was given a tuning fork to work with as his own project, but he assisted with the quartz oscillators and used the workshop to polish quartz plates before studying their properties. Three years after Essen joined NPL, Dye's death from pneumonia left Essen free to his own devices. He wrote up the tuning fork project and then carried on with the quartz oscillators. Essen made several important improvements over Dye's original design, making a smaller oscillator that could be more easily mounted, and shaped to make its harmonic frequencies independent of temperature. Using circuitry to divide the frequency into seconds, Essen found he had made a time-piece more accurate than pendulum clocks, which were still at that time the best form of timekeeping. Essen made six of his devices, including one for the Royal Observatory, although they decided to have their machine set to sidereal time rather than solar time. The Post Office adopted Essen's design, and arrangements were made to commercialise it. Dye's device provided the standard of time and frequency used at NPL from 1934 to 1936, and showed a stability of about 1 part in ten million. Essen's improved design was about a hundred times more stable, and provided the NPL standard from 1936 until 1955.

Watson-Watt, the inventor of radar, was head of the Radio Division at NPL, and as the war approached he needed a piece of equipment to test the properties of high-frequency cables. An electrical engineer was already working on the project, but Essen was tasked with approaching the problem in a different way. He soon had his own piece of equipment up and running, which proved effective and easy to use. This minor episode in Essen's career is indicative of his flair for making equipment work. He was very much at home in workshops and carrying out practical experiments. Essen's team made cavity wavemeters that could be used as frequency standards, but an engineering company that attempted to make them to the same design for sale found the work too difficult. Through his involvement in microwave electronics during the war, Essen saw that his cavity resonators could provide a new means of determining the speed of light c (for *celeritas*, the Latin word for speed).

Michelson and co-workers in the US had carried out a number of experiments to determine the speed of light using an evacuated tube a mile long. By the early 1940s, reviews of these experiments suggested that c was 299776 $\pm$ 4 kilometres per second. Essen was unimpressed that the claimed precision came from numerous repetitions of relatively inaccurate measurements, and he was convinced that a cavity resonator could provide a more reliable figure. William Hansen at Stanford University, an expert in cavity resonators, had similar ideas, but like Dye he too died from pneumonia before he could make much progress. Essen's first resonator designs yielded a value for c 16 kilometres per second faster than the accepted figure, to a widely sceptical response. The NPL Director at the time, Sir Charles Galton Darwin (grandson of Charles Darwin), suggested to Essen that his results would improve once he had perfected the technique. Essen used a number of cavity designs to eliminate the need to measure the length or diameter of the device, and these refinements gave exactly the same value for c he had obtained earlier, but reduced the error to one kilometre per second. The difference of 16 km/s may seem small, but it makes an important difference for navigation. Essen's figure was adopted by NASA, and in 1983 the International Committee for Weights and Measures agreed a value of 299792.458 km/s. At the same time, the metre was defined in terms of this value and the atomic second.

The experience that came with these microwave experiments, and the understanding of microwave refraction in air, allowed Essen and a colleague to develop the Mekometer, a measuring device allowing highly precise surveys to be carried out for work such as civil engineering. A senior member of the Ordnance Survey commented that the new machine allowed survey work that would have taken months to be completed in days, and this type of device is used worldwide in such work to this day.

The quartz clocks of the 1950s were accurate enough to show that the rotation of the Earth is not perfectly uniform. The problem, however, was that the frequency of a quartz oscillator depends on its size and shape, so what was needed for further improvement was a natural fixed frequency that could be used as a standard. The development of microwave techniques during the war enabled spectroscopic means to study the responses of atoms to electromagnetic radiation, and it became apparent that the single outer electron of alkali metals such as caesium[1] would make a useful standard. This idea was originally put forward by Isidor Rabi in the US, and the necessary spectroscopic methods were being developed by Jerrold Zacharias at Massachusetts Institute of Technology (MIT). Essen visited the MIT group in 1949, and, despite his own inexperience with spectroscopy, he decided to try making his own clock using caesium. There were no funds available for the project as NPL under Darwin was focussing strongly at the time on developing a new computer.

For several years Essen was obliged to work on other projects, such as improving the accuracy of the values for the speed of light and the refractive index of air for surveying work. As part of this work he spent time developing oscillators of suitable frequency with very limited bandwidth that he knew would be needed for measuring the caesium line accurately. When Essen visited America again in 1953 it seemed that one or other group there would soon have a working atomic clock. Harold Lyons at the National Bureau of Standards was managing a group of fifty staff dedicated to the project. Essen nevertheless felt that an independent device was important, and by this time NPL could make an assistant (Jack Parry) available, part-time, to help on the clock project. After a few months Essen and Parry had all the pieces they needed with the help of the NPL workshop. There were some difficulties with the atomic beam, but Otto Frisch at Cambridge, best known for his work on nuclear fission, suggested his former student Ken Smith (then at the Cavendish Laboratory) could help. Within two years Essen and Parry had their machine working, and within two weeks of operation they observed the fine structure of the spectral line they were looking for. Essen telephoned the Director on the 24th May 1955 to ask him to come over and witness the death of the astronomical second, and the birth of atomic time.

A few months after this event the International Astronomical Union met in Dublin, and, much to Essen's disgust, chose to adopt a new basis for the second using ephemeris time, which measures the rotation of the Earth around the sun. (Ephemeris time is not easy to measure, and requires years of astronomical observation.) Astronomers generally were not pleased to lose their role as time-keepers, and it was not until 1968 that the NPL standard was adopted internationally; even then the Greenwich Observatory abstained from the vote. In 1972 it was agreed to keep atomic time within a second of astronomical time by introducing leap seconds if required, and this system remains current today. Despite

[1]Caesium (the modern IUPAC spelling, formerly cæsium) is named after the colour of one of its spectral lines and *cæsius*, the Latin for blue-grey. The American spelling is cesium.

the funding available, early American efforts to produce a clock had been delayed by various problems, but NPL and Hewlett-Packard were making clocks by the late 1960s that were ten thousand times more accurate than astronomical time.

Given Essen's extensive scientific and technical expertise related to time-keeping, and his command of German, it might be imagined that he was a firm fan of relativity theory. He even met Einstein once, as Brose (an Englishman visiting Germany in 1914) had been interned during the First World War in Ruhleben camp near Berlin, with other British scientists such as James Chadwick. Einstein was a friend of several of these internees, and lived nearby. In 1930 Einstein visited the Nottingham group, with Brose translating his lecture into English. Essen was in fact very familiar with the type of problem described in Einstein's 1905 special relativity paper, of comparing clocks in different places, but it was not until after he had produced the atomic clock that he turned his attention to Einstein's work. He was not impressed. In his memoirs he mentions his surprise at finding Einstein's paper in some respects one of the worst he ever read. Einstein never made any experiments, and in Essen's words, "had no idea how to compare clocks".

Essen made his views on the subject clear – he felt that special relativity was inherently self-contradictory, and that his own obvious expertise in the subject would give him a hearing. On the second count at least, he was very wrong. He was invited to talk about relativity at the Royal Institution among many other academic institutes, and in 1971 Oxford University Press published a short pamphlet he prepared. The lectures he gave and the pamphlet resulted in many letters of congratulation and agreement from around the world. Essen did not heed hints from his superiors that his opposition to relativity could harm his career. He regarded science as a pursuit of truth and he was not dissuaded from offering his opinion on a topic that he rightly felt well-qualified to speak on. He felt that Einstein's theory was wrong, and that by heading down this path physics would be diverted from finding the real reason for the experimental findings that special relativity attempted to explain. (He believed the ideas of the French physicist René-Louis Vallée might prove a fruitful line of approach). Perhaps because of his reputation, Essen claimed never to have found a relativist who was willing to dispute with him.

Essen was a traditionalist who regarded truthfulness as the most important quality in a scientist. He placed clarity of expression second. Third, he felt that freedom for uninhibited criticism and discussion was essential for scientific progress. It is this third point where he clashed with the physics establishment. While there seems to be a widespread feeling that Essen's work in time-keeping thoroughly deserved a Nobel Prize, his persistent opposition to relativity may ultimately have denied him that recognition. Essen was awarded an OBE, and elected a Fellow of the Royal Society in 1960, among a number of important prizes. He enjoyed excellent relations with physicists in the US, and the Soviet Union, which awarded him the Popov Medal, a high honour indeed as he was the first non-Russian to receive it.

Essen retired to live in Surrey in 1972, and died in 1997, as unrepentant as ever about his views on relativity. Shortly before he died, his family persuaded him to write a memoir, which his son-in-law Ray Essen published in book form. It is a fascinating read. Very few people have had such a profound impact on the modern world as Louis Essen. If you are wearing a non-mechanical watch on your wrist as you read this, then you are wearing a direct descendent of one of Essen's devices. If you have passed over a bridge built since the 1960s, then you have indirectly used his microwave surveying machine. If you have flown in an aeroplane, or used GPS in a car, you have used navigational devices that are crucially dependent on his work in time-keeping.

Despite the incredible list of Essen's achievements, the accounts of those who knew him portray a very modest man. He was firmly socialist in his beliefs, perhaps not surprisingly given his upbringing by poor, hardworking parents in a time of strict class division. Personally, I was only made aware of Essen at all because one of his daughters happened to be my chemistry teacher at school, after she had given up her maiden name. As modest as her father, she made no mention of him at all during my school years. Many years afterwards I finally reached out to contact and thank her for her excellent lessons, which were still proving useful to me as the independent leader of a molecular biology research group. It was through this meeting that I discovered she was Louis Essen's daughter, and she kindly passed me a copy of her brother-in-law's book (the basis of this essay). So although I am glad to have found the time eventually to thank her, thirty years late, if I had been more prompt in my gratitude then there is every chance that I might have met the man himself, and, who knows, shaken the hand that changed time.

References

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