Institution:
Bangor University, 10007857

Unit of Assessment:
UoA12 – Engineering

Title of case study:
The development and implementation of a navigation and timing back-up to the Global Positioning System (GPS)

Period when the underpinning research was undertaken:
2000 - 2010

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
1) Professor David Last	1) Professor	1) June 1987 - March 2005, Emeritus March 2005 - 2020
2) Dr Paul Williams	2) Research Officer	2) June 1996 - February 2005

Period when the claimed impact occurred:
2015 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

The Global Positioning System (GPS) and other global navigation satellite systems (GNSS) are embedded in the world's critical infrastructure, from aviation and shipping to telecommunications and smart phones. Despite economic, social, and governmental dependence on satellite navigation and precise timing, GNSS are vulnerable to failure and security threats. Professor Last, and other members of the Bangor University Radio-Navigation Group, have worked with US, EU, UK and South Korean governments to develop and implement '*Enhanced Loran* (*eLoran*)' as a back-up in the event of GNSS failure. The UK, US and South Korean governments have directly invested in the development of technology developed collaboratively by Bangor, leading to a vital economic safety-net for mariners and cross-sector users in relation to trade and defence.

2. Underpinning research

Professor David Last was a world-leading and internationally renowned expert in the field of navigation. He led the Bangor University Radio-Navigation Group until his retirement in 2005, when he became a Bangor Professor Emeritus. He continued to work actively in the field by advising research groups, companies and governments. He was elected as President of the Royal Institute of Navigation between 2005 and 2008.

Led by Last, research at Bangor University focussed on terrestrial radio-navigation systems. Last was an international leader in developing several different radio-navigation systems, including Loran-C, marine radiobeacon Differential Global Positioning System (DGPS), Datatrak and eLoran; all designed to ensure the safe and effective navigation of maritime and land platforms. Many of those working in Last's team have subsequently made significant contributions in public and private sectors worldwide, for example Dr Dorothy Poppe, Fellow at the Charles Stark Draper Laboratory, Cambridge MA, USA.

Last's underpinning Bangor research, supported by Dr Williams, developed aspects of coverage modelling, channel optimisation, and system development and performance enhancement **[3.1, 3.2]**. For coverage modelling, a critical part of any radio-navigation system development, numerical analysis of signal propagation across a wide variety of environments (urban, rural,

marine) and conditions is required, in order to identify the optimal positioning of base stations and the corresponding user area. This was all done within the constraints of the regulatory framework and available spectral bandwidth. The research was then verified by designing, building and deploying test stations to provide experimental real-life performance data. The tool, techniques and knowhow developed by the group allowed them to undertake research that has subsequently been widely used internationally.

Seminal research was undertaken on the theory and application of Differential GPS to improve positioning accuracy, which was subsequently deployed in marine navigation. The group developed the frequency allocation algorithm, which was used to reassign the frequencies of all marine radiobeacon DGPS stations across Europe in 2001, an activity coordinated by the International Association of marine aids to navigation and Lighthouse Authorities (IALA), minimising the overall level of interference on any one frequency, resulting in greater system availability and improved safety to maritime navigation **[3.3]**.

A key long-term collaborator and funder has been the General Lighthouse Authorities of the UK and Ireland (GLA). Last and his team have been fundamental to the international development of Enhanced Loran (eLoran), and were the first to implement a large scale working prototype in the UK in 2015 **[3.4].** The Bangor group provided the essential technical expertise to ensure successful deployment with colleagues in the GLA, and worked closely with collaborations in Stanford University and the US Federal Aviation Administration to seek wider adoption of the concept. The eLoran system served enhanced maritime navigation and delivered precise timing for telecommunications users across the UK and beyond. Building on the long-standing and proven terrestrial low-frequency LOng-RAnge Navigation (LORAN) technologies, eLoran takes advantage of 21st century capabilities to meet the accuracy, availability, integrity and continuity performance requirements of maritime harbour entrance and approach manoeuvres, aviation non-precision instrument approaches, and land-mobile vehicle navigation. eLoran can also replace Global Positioning System (GPS) as the source of the nanosecond-level precise timing needed for mobile and fixed telecommunications, broadcasting and internet synchronisation. eLoran is an independent complement to GNSS, compatible in operation but dissimilar in its vulnerabilities **[3.5]**.

Though a little less accurate than GNSS, the high-powered, low-frequency, terrestrial signals of eLoran are much more robust and resistant to the jamming and deceptive spoofing now encountered than the extremely low-powered, microwave satellite signals from space. Providing an eLoran back-up allows users to retain the safety, security and economic benefits provided by GNSS when their satellite services are disrupted. Last was key in the system development in terms of his underpinning research, technical advice, and also through political engagement with governments and stakeholder groups, helping the world to recognise GNSS vulnerabilities at a time when most governments sought to dismiss such claims.

The expertise and reputation developed by the group led to both research and consultancy work covering a variety of application areas ranging from mobile phone base stations, the tracking of vehicles distributing cash to banks, the monitoring of marine buoys.

3. References to the research

3.1. **Williams, P**. and **Last, J. D.** (2000) Mapping the ASFs of the Northwest European Loran-C system. *The Journal of Navigatio*n, **53**(2), 225-235. DOI (Peer-reviewed journal article).
3.2 **Last, J. D.** and **Williams, P**. (2002) New sources of ASF data for European Loran users, Ortung und Navigation, Journal of the Deutsche Gesellschaft für Ortung und Navigation, 1, 119-134. (Copy available on request).
3.3 **Last, D**., Turhan, E. and Ward, N. (2001) Regional planning of DGNSS radiobeacon services. Navigation: *Journal of the US Institute of Navigation*, **48**(4), 247-254. (Peer-reviewed journal article).
3.4 **Last, J. D.** (2003) Is Loran C the answer to GPS vulnerability? *Journal of the Air Traffic Control Association* (USA), **45**(1), 17-22. (Copy available on request).

3.5. **Last, D.** (2010) GNSS: The present imperfect. *Inside GNSS*, **5**(3), 60-64.

4. Details of the impact

Implementation of a prototype for maritime navigation in the English Channel

The Dover Strait is the world's busiest shipping channel. Passenger and cargo vessels transiting through and crossing the Strait are highly dependent on Global Navigation Satellite Systems (GNSS) for their safe navigation in low visibility. Bangor researchers working with the General Lighthouse Authorities of the UK and Ireland (GLA), the body with statutory responsibility for maritime navigation, implemented a prototype eLoran radio navigation system as a back-up to Global Positioning System (GPS). This enabled ships to switch automatically and seamlessly between GNSS and e-Loran, so ensuring navigational safety. Using transmissions from legacy radio stations of the obsolete North-West Europe Loran C, plus a new eLoran station in Cumbria, the GLA provided an '*Initial Operational Capability'* eLoran service at Dover and 6 other key ports along the East Coast of the UK from 2014 to when the European eLoran stations were closed at the end of 2015 **[5.1, 5.2]**. The system demonstrated the performance of eLoran in an everyday, operational context, with receivers being used by mariners at sea. The performance met the International Maritime Organization's requirements for harbour approach, unequivocally demonstrating the benefit and cost effectiveness of the system. The total cost was approximately GBP5,000,000 and was a critical part of the process in developing the system beyond the prototype. This process was important for developing the prototype and has been the basis of the subsequent international standard **[5.3]**. Last was a Strategic Advisor to the GLA between 2005 and 2019 operating internationally **[5.1]**.

Impact on UK Government policy

Following a briefing in October 2016 of the Government's Chief Scientific Adviser (GCSA), to which Last and the GLA contributed, the Cabinet Office commissioned a study by London Economics which estimated the economic impact on the UK of a 5-day interruption of GNSS at GBP5,200,000,000 **[5.4]**. The study nominated eLoran as one of the "*most applicable mitigation technologies for the largest number of applications*" testifying to Last's policy impact and acceptance of the eLoran technology at a UK Government level **[5.4, 5.5]**. The Blackett Review **[5.6]**, published by GCSA in January 2018 recommended that the UK should employ GNSS-independent terrestrial radio systems, noting that eLoran met international maritime standards. A statement by the Cabinet Office Minister for Implementation reported that "*the UK Government is supportive of any progress towards initiating and maintaining an operational e-Loran network that can provide position, navigation and timing services and will lend support where appropriate to aid its establishment and continued use*" **[5.7]**. Last was actively involved in the development of the Blackett Review and subsequent government discussions since its publication, until the time of his passing in 2019.

Impact on US Government policy

As a result of Last's research and impact, global governments have realised the critical need to provide a back-up for GPS. Last delivered three invited briefings to the US cross-government Executive Committee's Advisory Board **[5.1, 5.8]**. The debate generated by the GLA's delivery of an '*Initial Operational Capability*' eLoran service contributed to two clear initiatives in the USA. In 2016 the House of Representatives unanimously approved legislation to create a GPS back-up system referring directly to eLoran **[5.9]**. In 2017 Congress voted for the National Defense Authorization Act, which enabled USD10,000,000 (12-2006) to be spent on a GPS Backup technology Demonstration. In 2019 and 2020 11 companies were selected to demonstrate their systems, with one company stating "*what is great about eLoran is there are no common failure modes between GPS and eLoran…what we are really focused on is helping the government reconstitute and deploy eLoran as a resilient co-primary back-up for GPS*" **[5.10]**. The National Timing, Resilience & Security Act of 2018 required a terrestrial back-up timing system to be established by December 2020; eLoran is the technology that best meets the specification set out in the Act and, based on its demonstrations, the US Government has opted to conduct further investigation into the problem. The starting cost estimated by Congress is approximately USD25,000,000 (12-2020) per annum. The US *SAE9990: International Transmitted Enhanced*

Loran (eLoran) Signal Standard (2018) is in place, establishing a blueprint for deploying eLoran. This technical standard sits within the International framework **[5.3]**, which Professor Last was instrumental in developing. Last continued to advise the US government until the time of his passing in 2019 **[5.1]**.

Development of eLoran in South Korea

Following a series of attacks by North Korea on South Korea's transportation and communications infrastructure using high-powered GPS jamming transmissions, the South Korean government is now developing eLoran as a backup system. System development is established and new eLoran broadcast stations have been implemented **[5.11]**. Last and former members of the Bangor research group, including Williams, who has been working for the GLA since 2005, acted as advisers and hosted high-level secondments in support of this initiative. Last and Williams provided invited government briefings in South Korea and worked until 2019 with the GLA and the eLoran equipment manufacturers, advising the South Korean government on constructing their system **[5.1, 5.11]**.

Prizes, awards, independent recognition and press coverage

Having served as the President of the Royal Institute of Navigation, Professor Last received the Harold Spencer-Jones Gold Medal of the in 2010. Last was awarded the prestigious Necho Award from the International Association of Institutes of Navigation in June 2015. He was presented triennially as a world-class leader in the field of navigation for "*navigation in general, over a number of years, and for a special achievement*". In 2018 he was elected a Fellow of the (US) Institute of Navigation, one of only two Fellows from the UK. Last was at the forefront of developing the legal and forensic aspects of Global Navigation Satellite Systems (GNSS). He was an expert witness in 136 legal cases (between 2013 and 2018), including high profile Home Office and Crown Court cases where GPS data was a compelling part of the forensic evidence **[5.12]**.

5. Sources to corroborate the impact

5.1. **GLA letter of support** (participant in the impact process). Corroborates Professor Last's critical role in developing the prototype eLoran system and his longstanding role as a Strategic Adviser to GLA and internationally.

5.2 **Offermans et al. (2015) "eLoran Initial Operational Capability in the United Kingdom – First results"**. *Institute of Navigation's International Technical Meeting, Dana Point, California, January 2015*. Provides evidence that the system was implemented and was co-authored by Williams (following his departure from Bangor and employment with the General Lighthouse Authorities of the UK and Ireland [GLA]).
https://rntfnd.org/wp-content/uploads/2015-ION-ITM-Offermans-eLoran-IOC-in-UK-final-4Feb.pdf

5.3 **IALA – G1125 – IALA Guideline: The technical approach to establishing a maritime eLoran service (2017)**. International standard detailing the technical approach to establishing a maritime eLoran service, which was developed from Professor Last and the GLA's prototype research for the EC.
https://www.iala-aism.org/product/g1125-technical-approach-establishing-maritime-eloran-service/

5.4 **London School of Economics (2017) The economic impact on the UK of a disruption to GNSS**. Report clearly supports the resilient PNT discussions at a UK government level and that eLoran is one of the "*most applicable mitigation technologies for the largest number of applications*" with over 90 references to eLoran. Professor Last's input on this assessment is clearly stated in the LSE letter below **[5.5]**.
https://londoneconomics.co.uk/wp-content/uploads/2017/10/17.3254_Economic_impact_to_UK_of_a_disruption_to_GNSS_-_Full_Report_FOR-WEBSITE.pdf

5.5 **Testimonial from London School of Economics, Associate Director (2020)** (participant and reporter in the impact process)**.** Testifies to Professor Last's research being pivotal in terms of assessing UK GNSS vulnerability and his wider research informing government and economists' work in this field.

5.6 **UK Government Blackett Review: Satellite-derived Time and Position - A study of critical dependencies**. UK Government Office for Science report detailing the national need to increase the resilience of critical services if GNSS is interrupted and the urgent need for back-up systems, featuring eLoran throughout the report. Professor Last is clearly listed in the expert panel on p.85 and his research is referenced on p.33.
https://navisp.esa.int/uploads/files/documents/5a8ff18f9edda807963168.pdf
5.7 **A statement from a Cabinet Minister** clearly demonstrates how eLoran is considered by UK Government as the viable technology to mitigate to GNSS vulnerabilities.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/677738/January_2018_Annex_B_-_MfGRE_to_Innovate_UK_re_eLoran__1__1_.pdf
5.8 **Minutes of the 21st meeting of the US National Space-Based Positioning, Navigation, and Timing Advisory Board (May 2018)**. Professor Last addressed the US Government in his role as GLA Strategic Adviser, the eLoran developer and in support of the UK work to understand the impact of GPS/GNSS vulnerabilities as per the Blackett review (p.3 and p.17).
https://www.gps.gov/governance/advisory/meetings/2018-05/minutes.pdf
5.9 **US Congressman John Garamendi's website** reporting on the bill passed by the House of Representatives and referring to eLoran as the ideal back-up system.
https://garamendi.house.gov/press-release/house-passes-strong-legislation-co-authored-reps-john-garamendi-and-duncan-hunter-gps
5.10 **Intelligent Aerospace article** quoting one of the companies the US government are working with to deploy back-up systems and who advocate the eLoran system **Hellens Systems and L3 Technologies**
https://www.intelligent-aerospace.com/home/article/14181475/eloran-loran-c-gps-gnss
5.11 **The International Association of marine aids to navigation and Lighthouse Authorities (IALA) technical report (30.05.18)** for the Ministry of Fisheries, Korea. Acknowledges Paul Williams along with the GLA, who Last frequently represented as their Scientific Adviser. It also cites Last's research **[3.1]** in developing the eLoran system.
https://rntfnd.org/wp-content/uploads/Korea-eLoran-2018.IALA_.pdf
The report was authored by Pyo-Woong Son et al., from Yonsei University and hosted on the **Resilient Navigation and Timing Foundation website**:
https://rntfnd.org/2018/06/04/eloran-in-s-korea-status-report-to-iala/
5.12 **Publicly available list of the police forces, law enforcement agencies and the Crown Prosecution Service** for which Professor Last carried out forensic analyses, prepared Expert Witness Statements and Exhibits, or appeared in court, with 136 records in the impact period 2013 – 2018.
https://scoop-cms.s3-eu-west-1.amazonaws.com/55dd7640ca2f3ade448b457d/experts/5763c7f7ca2f3af2228b6085/files/expert-witness-casespdf