Institution:	University of Oxford
Unit of Assessment:	9 - Physics
Title of case study:	[11] Absolute distance measurement

1. Summary of the impact

The performance of absolute distance measuring systems has been improved in terms of accuracy, traceability, reliability and cost through the introduction of new methodology arising from research at the University of Oxford. This has brought commercial benefit to a German company making measurement systems, through the creation of a new product line. New capabilities for measurement have been delivered to a first customer in Germany. The research has also resulted in the establishment of new activity at the National Physical Laboratory, and influenced UK and European technology roadmaps for future manufacturing.

2. Underpinning research

Particle physicists at the University of Oxford have had a fifteen year involvement with the development of detectors and accelerators that require precise alignment and monitoring, using frequency-scanning [laser] interferometry (FSI) of increasing sophistication. Two key projects laid the foundations for the impact described here.

ATLAS silicon inner tracking detector (R&D 1991-2002; installation 2003-07):
To monitor the positions of the many components of this detector for the Large Hadron Collider, a metrology system was required that was of sub-micron accuracy, very small, low mass, passive, radiation-hard, able to monitor hundreds of positions inexpensively and capable of remote operation. The Oxford ATLAS group proposed [1], developed, constructed and installed [2] a Frequency Scanning Interferometry (FSI) system consisting of a pair of lasers that drive a 'tree' of optical splitters each output of which feeds an interferometer, yielding an extremely scalable system. Using the two lasers alternately compensated for an error from drift during each measurement. Essential advances were a highly efficient data-acquisition system, a new way of manufacturing reflectors, and identifying a combination of suitable technologies for fibre splitters. In addition, given the operating environment, radiation-hard materials and fibres had to be identified and tested.

Linear Collider Alignment and Survey (LiCAS, 2002-9):
This project developed a robotic survey system (RTRS) for the 35km tunnel of a future linear collider (ILC). Dr Armin Reichold proposed a short train of measurement cars that can rapidly and automatically measure a network of reference position markers. The design objective was an accuracy of order 200 microns in the tunnel's straightness over 600 metres. A key step was the development by Reichold and his student John Green of a new data analysis technique based on least-squares spectral analysis (Lomb Periodograms) of the interferometer intensity data over time allowing simultaneous observation of multiple reflectors in a single interferometer. Other major achievements from this research were the ability to both feed light and read it out through a single fibre for the first time; the simultaneous presence of light from both lasers in the interferometers, eliminating the drift error completely; and collimation of the beam without generation of secondary reflection for long measurements up to 20 metres.

Having carried out market surveys to find photo diodes, lasers, and collimators with the required performance, the Oxford team realised that the system could be extended to longer distances and made significantly cheaper by adopting existing commercial telecommunications hardware. This meant switching to wavelengths around 1550nm and using InGaAs detectors. To adopt this approach, Reichold and his team developed compatible amplifiers with sufficiently low noise and high bandwidth and determined what specification of detector would be effective. The project culminated in a system that amplified a telecoms-class laser to operate 32 FSI interferometers simultaneously, which was deployed and tested in the RTRS at the DESY laboratory in Hamburg

[2]. This project was cut short after STFC's withdrawal from the ILC in 2007 but, motivated by the need for stable magnet positions in future linear colliders, the method was refined further, ultimately reaching nanometre precision interferometry for distances up to 10 metres.

Following these two particle and accelerator physics projects, the *Advanced Metrology Using Laser Tracers* project (AMULET, 2010-13), led by Reichold, then developed a new technique called dynamic FSI to give measurements that were both absolute and traceable [4,5], both essential attributes for industrial applications. The project was funded by EPSRC and two partners: the National Physical Laboratory (NPL) and the company ETALON-AG. A major advance was to use the molecular absorption frequencies in a gas cell as the primary traceable frequency standard, avoiding the cumbersome evacuated and thermally stabilised reference interferometers adopted in conventional approaches.

Other achievements by Reichold's group included

- A method to measure distances at every data point taken during a laser scan, enabling repeat rates up to the sampling rate of the analogue-digital converter (up to 2.77MHz for the main project and up to 50MHz for a prototype).
- Creation and evaluation of robust fibre-based reference interferometers that represent a temporary length standard and remain stable over the duration of an FSI scan (seconds); these massively decreased the overall size and cost of the system.
- Improvement of the vibration and drift tolerance of FSI.
- Optimisation of FSI system costs, in particular for the FSI lasers and reference interferometers.
- Exploitation of the new capability of a single FSI interferometer to observe several distances simultaneously for improved multidimensional coordinate metrology.

Participating researchers from the University of Oxford included lecturers Richard Nickerson (1989-present), Armin Reichold (1998-present) and David Urner (2004-10); PDRAs Steve Gibson (2007-10) and John Dale (2010-2013), both previously students, Paul Coe (2009-10), Patrick Brockill (2008-9 and 2011-13), and Grzegorz Grzelak (2003-8); and students John Green (2004-8), Matthew Warden (2006-12) and Andrew Lancaster (2010-present).

3. References to the research (Oxford authors underlined; * denotes best indicators of quality)

1. A.F. Fox-Murphy, D.F. Howell, R.B. Nickerson and A.R. Weidberg (1996). Frequency Scanned Interferometry (FSI): The basis of a survey system for ATLAS using fast automated remote interferometry. *NIM A* **383** 229-237. (7 citations, Scopus) doi:10.1016/S0168-9002(96)00617-1 *This was the first paper on FSI for ATLAS.*

2. *S.M. Gibson, M. Dehchar, K. Horton, A. Lewis, Z. Liang, S. Livermore, C. Mattravers and R.B. Nickerson (2010). A novel method for ATLAS FSI alignment based on rapid, direct phase monitoring. ATL-INDET-PROC-2010-037, ATL-COM-INDET-2010-114 http://inspirehep.net/record/1196730/files/ATL-INDET-PROC-2010-037.pdf *This conference paper presents the results from operation of the FSI system at ATLAS, providing continuous measurements every 8 seconds, with a sensitivity of <50 nanometres over 24 hours. Gibson worked on this project in Oxford and thereafter moved to CERN .*

3. A. Reichold, P. Brockill, S. Cohen, J. Dale, M. Dawson, T. Handford, M. Jones, G. Moss, L.A. Rainbow, M. Tacon, C. Uribe-Estrada, D. Urner, R. Wastie, S. Yang, J. Prenting, M. Schlösser and G. Grezelak (2008). First data from the Linear Collider Alignment and Survey Project (LiCAS). 11th European Particle Accelerator Conference, Genoa, June 2008. http://epaper.kek.jp/e08/papers/tupc118.pdf *This paper presents the design criteria and performance of the tunnel survey robot (using FSI technology) installed at DESY, Hamburg and developments in analysis software and understanding of systematic calibration and errors. Other authors, from DESY and Warsaw, are members of the LiCAS collaboration.*

4. *D. Urner and M. Warden (2012). Apparatus And Method For Measuring Distance. Patents WO2012022955 A1 and US20130148129 A1 (filed 22/7/2011).

http://worldwide.espacenet.com/publicationDetails/biblio?CC=WO&NR=2012022955A1&KC=A1&FT=D

5. *J. Dale, B. Hughes, A. Lancaster, A. Lewis, A. Reichold and M. Warden (2013), An absolute distance measurement system using frequency scanning interferometry and gas absorption cells. Confidential report submitted to ETALON, 28th October 2013 (available on request).

4. Details of the impact *(references e.g. [A] are to sources in section 5)*

Laser tracers and laser trackers are widely used for high accuracy, large-scale dimensional metrology, for example in the calibration of CNC and CMM machines. In 2010, the best such instruments used differential interferometry for high accuracy displacement measurements, necessitating either continuous observation of a single target, or the use of much lower accuracy absolute distance meters. The AMULET project broke these limitations, by equipping a prototype laser tracer with dynamic FSI to perform *absolute* distance measurements with accuracy comparable to that of differential interferometry and with other user benefits as described below. The National Physical Laboratory, as one of the partners in the project, tested the dynamic FSI technology and confirmed sub-part-per-million accuracy at up to a 20 metre range [A].

Isis Innovation, the University of Oxford's technology transfer office, filed two patents [4] for the FSI system in July 2011, which were licensed to ETALON-AG in 2012. ETALON identified the FSI technology as, "*a pioneering solution to the precision measurement of absolute length*" [B].

New capabilities in absolute distance metrology

The dynamic FSI approach allowed the tracer to be tolerant to beam breaks and to automatically switch targets. ETALON describe some of the advantages of dynamic FSI being that it allows traceable measurements with a "*10,000 times faster time resolution and 20 times higher accuracy*" than previous absolute distance systems; that it "*recovers gracefully"* from beam breaks and does not require frequent calibration.

Dynamic FSI systems can also be scaled up to make many hundreds of measurements for only a small fractional increase in cost compared to the basic system, simply by using multiple interferometers whose components are cheap. ETALON have identified that together with being "*cheaper to manufacture than previous technologies",* this makes their "Absolute Multiline™" range of FSI products *"relevant and accessible to a much wider range of purchasers*" [B]. ETALON describe their market areas as "*the calibration, monitoring and accuracy enhancement of machine tools and measuring machines*", with customers from the mechanical engineering, metrology, automotive and aerospace industries, as well as from research sectors.

New product brought to market

The Absolute Multiline™ system launched in November 2012 [B] became ETALON's primary FSI-based product. It is a general purpose, absolute distance interferometer system marketed as having up to 100 measurement channels and distances between the sensors and system electronics of up to several kilometres. ETALON's marketing material describes another advantage of the system as being that, "*The sensor signals are not affected by electromagnetically noisy environments; therefore the placing of sensors in e.g. energy chains is possible without the degradation of performance*" [C]. The list price of the basic product ([text removed for publication]) with software is in excess of [text removed for publication].

ETALON's development of the FSI system into a product was accelerated by research and consultancy contracts undertaken by Reichold and his team at Oxford, which ETALON identify as *"drawing directly on knowledge and experience from their research*" [B]. ETALON-AG secured funding from the Lower Saxony Development Bank, NBank, to build a prototype Absolute Multiline™ system for marketing and user training purposes. In total, ETALON have invested [text removed for publication] in developing and marketing the Multiline system. This included not only manufacturing the prototype but also demonstrating it at trade shows in Chester, Stuttgart and San Diego. They have stated that they wish to *"make Multiline one of the cornerstones of our* *business".*

The first of these systems, with 24 channels, was built at Oxford and later repackaged by ETALON. This system was sold to the Metrology and Quality Management group at RWTH Aachen, and installed and commissioned in June 2013. The group leader at Aachen stated that the system "*significantly enlarged"* their capabilities in the field of large volume metrology and that they were *"not currently aware of any other system on the market that [Aachen] could have purchased to achieve the same performance".* Their most challenging application at July 2013 had successfully achieved ten simultaneous absolute distance measurements over distances up to 6m [D]. By July 2013, a second sale had been agreed to the metrology group at the SLAC National Accelerator Laboratory in the USA.

New budgeted programme and employees at the National Physical Laboratory

NPL is the UK's national measurement institute, operated commercially under contract to the National Measurement Office. As a direct result of their participation in the AMULET project, NPL decided to establish their own FSI group including a research programme valued at around £700,000 [A]. By July 2013 this included appointing two new, full-time members of staff, one of whom was Dr Warden, who left the Oxford group to take up that post. As another benefit, NPL realise licence revenue from any sales of Absolute Multiline™ and thus receive financial benefit from the systems sold by ETALON.

Influence on policy via technology roadmaps

One of the themes within NPL's future vision, 'Metrology for the 2020s' (published in March 2012), is 'embedded and ubiquitous measurement': within this theme, laser interferometry systems for accurate and traceable metrology were identified as having an important contribution to future processing and production [E]. NPL state that the FSI work will be instrumental in delivering some of this vision. NPL also identify the inclusion of FSI on two roadmaps as resulting directly from AMULET [A]:

- The UK National Measurement Office draft Large Volume Metrology roadmap 2011-19 [F], which forms part of the Engineering and Flow metrology programme of the governmental Department of Business, Innovation and Skills.
- The European Association of National Metrology Institutes (EURAMET) Technical Committee for Length's roadmap for Large Volume and Long Range Dimensional Metrology, published in June 2012 [G].

5. Sources to corroborate the impact

A. *Performance of dynamic FSI system, attribution of impacts to Oxford's research and changes to NPL's programmes*: Science Area Leader, Dimensional Metrology and Lead Scientist, Large Volume Metrology, National Physical Laboratory, letter held on file.

B. *Activities, expenditure and benefits to ETALON-AG*: CEO of ETALON, letter held on file.

C. *Multiline marketing*: http://www.etalon-ag.com/index.php/en/products/multiline

D. *Purchase, installation and performance of first system sold:* Chief Engineer, Laboratory for Machine Tools and Production Engineering, RWTH Aachen University, letter held on file.

E. 'Metrology for the 2020s' vision, http://www.npl.co.uk/2020vision/

F. *Inclusion of FSI in draft NMO Large Metrology Roadmap 2011-19*: copy held on file.

G. *Inclusion of FSI in EURAMET roadmaps*, June 2012, http://www.euramet.org/index.php?id=roadmaps, especially Large Volume and Long Range Dimensional Metrology: http://www.euramet.org/fileadmin/docs/Publications/roadmaps/TC_L_Long-range_Roadmap_2012_text.pdf