Institution: University of Oxford	
Unit of Assessment: 9 - Physics	
Title of case study: Absolute Distance Measurements from particle colliders to high value manufacturing	
Period when the underpinning research was undertaken: 2002 – 2020	
Details of staff conducting the underpinning research from the submitting unit:	

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
Professor Armin Reichold	Professor of Particle Physics	1998 – present
Professor Richard Nickerson	Professor of Particle Physics	1989 – present
Dr John Dale	PDRA	2010 – 2013
Dr Andrew Lancaster	PDRA	2015 – 2017

Period when the claimed impact occurred: 1st August 2013 – December 2020

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

1. Summary of the impact (indicative maximum 100 words)

Professor Reichold co-developed and patented advanced Frequency Scanning Interferometry (FSI). Initially this technology underpinned the operation of the ATLAS detector at CERN's Large Hadron Collider, and ultimately it became the world's most accurate commercial instrument for absolute distance measurement. Prof. Reichold commercialised the technology through collaboration with Etalon, who manufacture and sell the Absolute Multiline product for industrial and scientific applications with sales in excess of GBP3,000,000. The technology's data acquisition elements have been further developed in collaboration with VadaTech UK, who now produce the MicroTCA-based (Micro Telecommunications Computing Architecture) DAQ (Data Acquisition) system, which includes a novel optical receiver circuit board developed at Oxford Physics. Manufacturing companies using Absolute Multiline have benefitted from the significantly improved manufacturing accuracy that this system enables. Furthermore, industrial metrology standards have been improved through its deployment at national standards laboratories (NPL, PTB, le cnam, INRiM), thus benefitting a wide range of organisations by improved calibration. The success of this technology has influenced European National Metrology Institutes (NMI) to devote significant resources to explore how industry can maximally benefit from further FSI development.

2. Underpinning research (indicative maximum 500 words)

ATLAS Silicon Tracking Detector (SCT, 2003 – 2007):
A metrology system of sub-micron accuracy was required to monitor the positions of components of the semiconductor tracker at the Large Hadron Collider. To satisfy the extreme constraints imposed by the environment of a particle physics collider experiment, it had to be very small, low-mass, passive, radiation-hard, inexpensive, and able to simultaneously monitor 842 distances remotely. To meet this need, the Oxford ATLAS group proposed, developed, constructed and installed [1,3] an extremely scalable FSI system. To achieve this, they made essential advances in FSI technology: they developed a highly efficient data-acquisition system, and a new technique for manufacturing miniature reflectors and launch optics.

Linear Collider Alignment and Survey (LiCAS, 2002 – 2009):
This project developed a robotic survey system for the 35km tunnel of a future linear collider (ILC). Reichold proposed the Rapid Tunnel Reference Surveyor (RTRS) – a short train of measurement cars that can rapidly and automatically determine the 3D positions of a network of reference markers with sufficient accuracy to determine the straightness of the accelerator to 200 microns over any 600m long segment. This requires a sub-micron accuracy on individual distance measurements made by the RTRS. One key step was the development by Reichold of a new FSI data analysis technique using Lomb Periodograms allowing simultaneous observation of multiple reflectors in a single interferometer. Other major achievements were the ability to feed light in and read it out through a single fibre. A further novel feature was the use of two lasers which simultaneously scanned their frequencies in opposite directions. This completely eliminated the effect of variations in the measured

distance during the measurement, which would otherwise generate errors of about 20 times the size of the drift. Cost efficient beam collimation and the use of Erbium-doped fibre amplifiers has extended the measurement range to 20 metres. The improved system provided sufficient capability for 36 simultaneous distance measurements. The RTRS was deployed and tested in a tunnel at the DESY laboratory in Hamburg [2]. The RTRS was the instrument that first caught the interest of future industrial collaborator Etalon.

Advanced Metrology Using LasEr Tracers project (AMULET, 2010 – 2013):
Following the above two particle and accelerator physics projects, the AMULET project, led by Reichold, then developed a new technique called dynamic FSI to give measurements that were both absolute and traceable [4] (both these attributes are essential for industrial applications). The project included two partners: The National Physical Laboratory (NPL) and Etalon. A major advance was to use the molecular absorption frequencies in a gas cell as the primary traceable frequency standard. The new dynamic-FSI technique was able to measure distances at a repetition rate of 2.7 MHz (54,000 time faster than the original ATLAS system) which enabled its use in high-speed vibration measurements. The new DAQ system was also much more compact (more channels per unit volume) which is of crucial importance for industrial applications. The development of AMULET was the key step that enabled FSI to be used in absolute distance multilateration systems (multilateration is the measurement of coordinates through distances alone) which play an essential role in current approaches to large-volume metrology by National Metrology Institutes. AMULET led directly to the licenses underpinning Absolute Multiline Technology.

FSI Upgrades (2014 – 2015):
Oxford Physics manufactured the original DAQ (Data Acquisition) systems for Etalon but given increased sales it was no longer feasible to continue manufacture. Applications in accelerators require extended bandwidth with real-time readout and the capacity for remote management since the DAQ systems are often inaccessible. To address these demands a collaboration with VadaTech UK was established to produce a cost-efficient multi-channel DAQ system by combining commercially available µTCA.4 (micro Telecommunications Computing Architecture) components with custom optical receiver boards developed at Oxford which transfer data into a host PC via a PCIe bus extension. The increased bandwidth of 67 MHz (up from 1.3 MHz) and decreased acquisition time jitter of sub 1 microsecond (down from several milliseconds) enables uses in fast real time feedback systems.

Phase Modulation Interferometry (PaMIr, 2016 – present):
Phase Modulation Interferometry as developed by PaMIr allows the unambiguous determination of *displacements* (rather than absolute distance) using a phase-modulated laser beam with only a single detection of the interference intensity, and is backward compatible with the FSI hardware. The current Multiline technology has a latency between 0.1 and 1 seconds and can measure targets moving at speeds below 19 mm/s. However, many industrial applications need to measure faster moving targets, and with much lower latency to enable machine tool feedback. FSI already scales cost effectively to multiple simultaneous measurements, and targets located up to several km from the central system can be measured, making it highly attractive for large-scale deployment, e.g., many CNC (Computer Numerically Controlled) machines in a single factory, but it lacks real-time capability. Reichold and his team developed the PaMIr method which extends FSI to low-latency (1 microsecond) measurement of highly dynamic targets (up to 1 m/s). It preserves the attractive features of FSI, such as simultaneous measurements of many distances with a low cost per measurement channel. This compatibility allows combination of absolute distance measurements via FSI, with tracking high-speed objects using the PaMIr method. Even if the beams are broken, absolute target positions can be re-established without needing to return the reflectors to reference positions. This feature results in a substantial reduction in time spent on recovering from errors.

3. References to the research (indicative maximum of six references)

1. The ATLAS Collaboration et al (2008) (inc. R Nickerson). The ATLAS Experiment at the CERN Large Hadron Collider. JOURNAL OF INSTRUMENTATION, 3. doi:10.1088/1748-0221/3/08/S08003.
2. 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
3. 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
4. Dale J, Hughes B, Lancaster AJ, Lewis AJ, Reichold AJ, Warden MS (2014), Multi-channel absolute distance measurement system with sub ppm-accuracy and 20 m range using frequency scanning interferometry and gas absorption cells. Optics Express, 22(20):24869-24893]. https://doi.org/10.1364/OE.22.024869

4. Details of the impact (indicative maximum 750 words)

Industrial need for FSI Technology

In modern industrial societies length measurements are deeply embedded into all production processes. Requirements for range, resolution, speed and absolute accuracy are constantly becoming more stringent. One important and demanding application is the control of CNC mills or lathes. CNC machining heads move at high speeds (m/s). Position control requires rapid, simultaneous measurement to micron resolution of dozens of absolute distances in the sub-mm to tens of metres range. Commercial FSI has a distance range of 30 m, measurement uncertainty of 0.5 ppm and high sampling rate of 125 MHz on up to 96 simultaneous channels, making it the ideal technology for calibrating CNC machines. Furthermore, FSI sensors are robust (unaffected by electromagnetic interference), compact (no moving parts), and can be positioned several kilometres from their central electronics. This enables measurements under extremely rough environmental conditions, such as those found in the UK Nuclear Advanced Manufacturing Research Centre (NAMRC) in Sheffield where highly radioactive materials are being processed. Unlike competing conventional interferometers, FSI beams can be interrupted without loss of precision: absolute distance measurement is resumed fractions of a second after an interrupted beam is restored. FSI length measurements are non-contact and traceable to the SI metre, making this technology highly suitable for in-situ metrology systems, as piloted at the German national metrology institute, PTB. FSI offers improved accuracy for multilateration compared to traditional sequential kinematic measurements and is being developed by national metrology institutions (NMIs) across Europe.

In an effort to bring FSI technology into a product form suitable for the largest range of applications and to make it known and available to the maximum range of customers Reichold teamed up with industrial partner Etalon and later also with VadaTech UK. Etalon offers high-end system solutions for the calibration, monitoring and accuracy enhancement of machines, robots and structures. Etalon customers include companies from mechanical engineering, industrial instrumentation, automotive and aerospace technology and the research sectors. Etalon licensed Oxford's FSI technology and initially invested EUR200,000 to bring it to the market in the form of Absolute Multiline [**A**], a universal and highly configurable metrology toolkit [**B**]. VadaTech is the world's largest manufacturer of MicroTCA systems and the only vendor that develops and manufactures all elements of the MicroTCA infrastructure in-house. Between 2014 and 2018, Oxford, in collaboration with VadaTech, developed the second generation DAQ system for Absolute Multiline on the MicroTCA platform.

Applications of Etalon's Absolute Multiline [A]

Manufacturing industry customers of Absolute Multiline include:

- **Safran Reosc**: Metrology system enabling Safran to measure the absolute shape of mirrors during manufacture of the 900 mirror segments of the primary mirror of the European Extremely Large Telescope with a measurement uncertainty < 20 nm.
- **Siemens**: Deformation monitoring of *BorWin Gamma* (a EUR1,000,000,000 AC to DC offshore converter platform) during its loading, transfer and deployment from the shipyard in Dubai to an offshore wind park in the North Sea. This ensured that any deformations that could damage the sensitive electrical installations on the platform could be detected and remedied prior to commissioning.
- **General Electric**: Gas turbines are highly loaded structures with extremely tight tolerances. Absolute Multiline systems are used to monitor the distortions of turbines in test runs at General Electric to indicate possible problems.
- **DMG Pfronten**: Monitoring of thermal deformations of DMG's CNC machines.
- **Heidenhain**: Monitoring of thermal deformation of machine tools and development of new methods for calibration of glass ruler manufacturing.

Research Technology Organisation customers using Absolute Multiline include:

- **UK NARMC (Nuclear Advanced Materials Research Centre)**: System used for a facility-wide metrology network for the calibration and monitoring of large coordinate measurement machines and machine tools for the ultra-precise manufacturing of large components for the next generation of nuclear reactors.
- **PTB (Physikalisch Technische Bundesanstalt, Germany**): Purchase used for multiple purposes: (i) calibration and monitoring of a test rig for mobile metrology instruments, (ii) calibration and monitoring of a large ultra-precision Co-ordinate Measuring Machine (CMM) and (iii) measurements of deformations for a torque test stand for wind energy.
- **University of Dresden**: Bought to identify the deformation of robots, machine tools and presses. This purchase allows new approaches for assuring dimensional stability of manufacturing processes (Industry 4.0). Industry 4.0 automates traditional manufacturing and industrial practices, using modern smart technology and metrology.

Impact on Etalon [A]: Etalon currently holds five licences from Oxford University. Etalon have sold Absolute Multiline products since 2013 with a total value of GBP3,267,000 (22 individual sales) of which GBP3,113,000 occurred since August 2013, accounting for 15% of Etalon's business, supporting three full-time positions at Etalon. The list price for the products with software ranges between GBP30,000 and GBP430,000 depending on the number of channels and non-recurring engineering prices for customer specific elements. Since 2015 Etalon have invested GBP240,000 on continual upgrades of the technology in collaboration with us. The success of the Absolute Multiline contributed significantly to the decision of the global Hexagon corporation to acquire Etalon in January 2019.

Impact on VadaTech [C]: Since May 2019 the Absolute Multiline DAQ elements are commercially available and have seen sales of approximately GBP600,000. The Managing Director of VadaTech Ltd describes the impact of our work on VadaTech Ltd in the UK as follows: "*Due to our collaboration with Oxford Physics, the UK office has been able to drive product development in both USA and Taiwan to meet specific requirements of our European customers. Since we did not directly fund that development, we gain value from the resulting engineering work. UK-based product development marks a paradigm shift for VadaTech [the mother corporation of VadaTech Ltd] that allows the company to develop product ownership here in the UK, which strengthens UK control of VadaTech's strategic direction... Business at VadaTech Ltd. derived from our collaboration with Oxford currently supports 50% of one engineering position and led to local manufacturing partnerships that are now proving useful across a wider product range.*"

Further investments to increase impact of FSI, 2018 – present [A,C]: As described at the start of this section, CNC manufacturing machines are the key drivers of metrology requirements in industry. Etalon estimated the potential market share of a suitably enhanced Absolute Multiline technology to be EUR1,000,000 - EUR2,000,000 per annum by 2024.

Although the old Absolute Multiline technology was too slow for real-time operation (thus was limited to being used for calibration only), its inherent scalability, low-cost front-end hardware and large channel count made it highly suitable for such an extension. The proof of principle work done in preparation for the PaMIr project and PaMIr's initial studies convinced our commercial partners to invest in the development of these extensions in 2018. Etalon invested EUR280,000 (their annual turnover is EUR3,240,000). Commenting on the PaMIr project, the Managing Director of VadaTech Ltd said, "*VadaTech has invested GBP103,500 into PaMIr. We are also committed to recruit the project's senior electronics engineer, now employed at Oxford, at the end of his contract*".

Influencing Industry via European National Metrology Institutes (NMI) [D]

One of the key roles of NMIs is the provision of the fundamental data and standardisation processes enabling the traceability of metrological measurements to the SI system of units, which is critical for measurement technologies in industry. NPL is the UK's NMI, developing and maintaining the national primary measurement standards and is a Public Corporation owned by the Department of Business, Energy and Industrial Strategy (BEIS). The European NMIs identified FSI as one of the most important themes for Europe's future Large Volume Metrology (LVM), because of its ability to measure the size, location, orientation and shape of large objects, assemblies or machine tools. These are critical requirements in many high value industries where the UK and EU are globally competitive, such as aerospace, automotion, civil engineering, and power generation. LVM is also an underpinning technology used in critical periodic alignment of large advanced science facilities such as those at CERN or ESRF, in preparation for particle beam-based therapy systems for healthcare, and in the civil engineering and surveying industries. NMIs affirmed the importance of FSI in the current EMPIR (European Metrology Programme for Innovation and Research) project called LaVa (2018-2021) and its successor DynaMITE (2022-2025), both of which focus on FSI as one of the key technologies for future LVM. These projects are the strategic innovation initiatives of European NMIs and address the industrial need for more accurate, large volume coordinate measurements. The Science Area Leader, Dimensional Metrology of NPL, describes the impact of Oxford-NPL-Etalon research **[4]** on FSI on the strategic direction of European NMIs as follows: "*The successful outcome of the AMULET project showed us that FSI is an extremely powerful and adaptable measurement technique that is applicable to many scenarios outside the research lab and can easily be made traceable to the SI metre. The positive outcome of AMULET has informed and influenced the decisions of NPL and other European NMIs to focus parts of their research in large volume metrology on those extensions of FSI that would maximally benefit industry needs. More specifically, the FSI related work in LUMINAR focussed on the development of OPTIMUM for industrial applications in, for example, the aerospace industry. DynaMITE will extend this capability to dynamic coordinate measurement for metrology assisted robotic machining and assembly applications. And, LaVA is aiming to provide the most accurate measurements to date of the spectrum of HCN such that it can be ratified by the Consultative Committee for Length as a secondary realisation of the metre, thus enhancing SI traceability of FSI. In another recent development, we have used FSI to make the first measurement of the separation of gridded ion thruster acceleration grids while the thruster is in operation – the so-called 'hot gap'. This measurement provided a crucial validation of the theoretical performance of this critical operating parameter which affects the overall efficiency and lifetime of the engine. Our measurement was instrumental in convincing ESA that the ion thrusters developed for the BepiColumbo mission were fit for purpose and would be capable of performing the 14 months continuous deceleration burn on the approach to Mercury*".

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Letter from Managing Director, Etalon, includes list of customers and applications

B. https://www.etalonproducts.com/en/products/absolute-multiline-technology/ Product webpage of Absolute Multiline

C. Letter from Managing Director, VadaTech Ltd

D. Letter from Departmental Head of Science, Science Area Leader, Dimensional Metrology, National Physical Laboratory, UK