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1 Executive Summary

1.1 Introduction

The project has successfully tackled the most critical needs expressed by a range of users of Large Volume Metrology (LVM) by developing a range of new dimensional measuring instruments, new ways of compensating for thermal and refractive index distortions, new measurement facilities and updated modelling software, all designed for *in situ* operation in large volumes. The new (prototype) instruments have been developed, inter-compared and successfully tested and demonstrated in both laboratory and industrial locations. The instruments are based on a range of different principles, targeting different application areas. Outputs from the project include instruments, techniques and new knowledge as well as many technical publications and presentations and five patents (two of which are already granted). Selections of stakeholders have already expressed a desire to use or further develop several project outputs and opportunities for commercial and scientific exploitation (*i.e.* as commercial instruments or collaboratively developed facilities) are already under discussion with a range of organisations. Some of the new facilities, such as the improved 50 m tunnel are already available.

1.2 The Problem

In many high value industries and science & healthcare facilities, large objects, assemblies, equipment and facilities are manufactured or used, often at high cost. In order for these to operate correctly, control of position, dimensions and/or shape of key components at the tens of micrometres level has to be performed within large volumes (hundreds of m³), often in non-ideal environments. Better measurement generates significant advantages such as: better accuracy of aircraft wing and fuselage manufacturing reduces the amount of excess material required ('shim') saving weight and fuel-burn, and enables more aerodynamic designs to be achieved (*e.g.* natural laminar flow for better fuel efficiency); better traceability to the SI ensures compatible component dimensions (*e.g.* airframe sections) when sourced from multiple countries (*e.g.* Airbus operational model); particle accelerators (*e.g.* CERN's Large Hadron Collider) and advanced energy experiments/facilities (ITER, ESRF) as well as beam-based therapy systems in healthcare require alignment of components over hundreds of metres to hair-width tolerances in order to function. In all these scenarios, the measurement is not performed at a laboratory, but on the shop floor, *in situ*, in non-controlled environments, making it difficult. To achieve these requirements, users of so-called Large Volume Metrology (LVM) systems require these systems to: measure structures which are at uncontrolled temperatures and compensate for thermal expansion; cope with large measurement datasets with low uncertainties and ideally at high speed and low cost; compensate for errors introduced by airborne refraction; provide dimensional traceability to the SI metre; be portable; and ideally assist the operator in calculating the total achieved measurement uncertainty. LVM makes use of a number of optical techniques (laser tracking, photogrammetry, interferometry, *etc.*) to determine position and dimensions of large objects but existing commercial LVM tools cannot achieve all or even some of these requirements, across all ranges and technologies. A consortium of end users identified and collated their key issues with LVM and the top four issues became objectives for this research project. (Other issues were left for future work).

1.3 The Solution

In order to address as many issues as possible we decided that multiple strands of research were necessary with the goal of developing several new techniques and instruments – we thought it unlikely that a single approach would deliver impact for all end users. Firstly, we decided to develop several new measuring instruments to full prototype stage, based on different operating principles. To combat the 'black box' approach now being embodied in proprietary absolute distance meters (ADMs) used in commercial laser tracker and laser ranging devices, we targeted a second research theme at developing ADMs which provide easy to verify traceability routes using either well-known laser traceability schemes or using cheap, off-the-shelf components. To enable better accuracy operation in non-standard environments we aimed to develop both along-the-beam refractive index compensation and wider field refraction detection and modelling. The environment not only affects the measuring instruments but also the object/assembly being measured – a fourth research strand aimed to model and compensate for thermal distortion of assemblies in non-ideal environments. To ensure that all the research outputs were performing as intended and that they were capable of operating in industrial location, a final series of intercomparisons and demonstrations was planned including a live test of several project outputs at an operating Airbus facility.



By the end of the project, we had delivered:

- (1) A prototype system based on an intersecting planes technique (*InPlanT*) which uses linear axes separated from the harsh environment.
- (2) A prototype system similar to videogrammetry but using spherical targets and through-the-lens laser illumination.
- (3) A system based on frequency scanning divergent beam interferometry which demonstrated an accuracy of 50 μm over small (1 m^3) volumes. This system was then developed further into:
- (4) A longer range system, again using frequency scanning interferometry (FSI), which was demonstrated at 10 m ranges in laboratory and industrial environments.
- (5) A portable telemeter based around cheap off-the shelf components operating at 1550 nm and 785 nm wavelengths which could measure over ranges of 50 m and perform along-the-beam refractive index correction using the second wavelength.
- (6) A tracking interferometer with absolute distance determination based on multiple wavelength interferometry, together with an additional set of wavelengths for refractive index compensation.
- (7) An upgraded 50 m tape bench facility with additional temperature, pressure and humidity sensors together with heating circuits, to simulate an industrial environment.
- (8) A range of photogrammetry tools (multi-spectral imaging, long focal length imaging, digital axicon camera, MathCad refraction analysis, volumetric refractive bundle adjustment software) developed and combined into a system which can perform photogrammetric analysis of images and discrete thermal measurements with refraction modelling and signal environmental instability across large volume manufacturing spaces.
- (9) A hybrid thermal compensation scheme in which scheme data from a sub-set of dimensional measurements is fed back into a finite element model analysis together with temperature data, to iteratively improve the accuracy of the FEA simulation. The model can then be used to perform thermal compensation of the entire assembly/structure.
- (10) A test component/assembly, typical of those used in aerospace manufacturing, designed and instrumented together with full CAD model.

An inter-comparison of outputs (5) and (6) was performed using facility (7). This allowed verification of the ultimate accuracy of these new instruments. Output (4) was taken to and tested in the Reference Wall facility at PTB, allowing a test of the technique's ultimate accuracy in a good environment. Industrial testing/demonstration of outputs (1), (4), (5), (6), (8), (9) and (10) took place at Airbus, Filton, UK in a live factory environment. The work of the project team has been presented at over 30 conferences, several sets of training have been delivered by the project team, ten peer-reviewed journal papers have been submitted and one good practice guide produced.

1.4 **Impact**

The project has already demonstrated impact and interest from end users across a selection of fields and this has been growing in momentum. However, the greatest impact will occur when the project outputs have been developed into commercial instruments and when discussions on future collaborations have culminated in new collaboratively developed facilities such as that being discussed with CERN.

Dissemination

Ten publications have been submitted to peer-reviewed journals (five already published) and we have made twelve inputs to standardisation and metrology committees (EURAMET, ISO, VDI/VDE, UNI) with one standard already citing work from the consortium partners. The project work and outputs have been presented at 32 conferences and project staff have given eight training sessions (six of which were for external audiences of end users). Three trade journal articles have been used to publicise the work in industry and we have conducted a two week long successful onsite measurement and demonstration campaign at Airbus, Filton as well as two successful inter-partner measurement campaigns.

Early impacts

Five patents have been submitted based on the work of the project and two have already been granted: DE 10 2010 032 407 B3 and DE 10 2015 203 697. These patents have been the basis of two project partners entering into partnership discussions with two commercial organisations, to exploit the developed technology; a partnership agreement is close to signature. An existing €0.5M collaboration with the University of South Wales changed direction as a result of the project (*i.e.* the project outputs showed a better route for the



research direction). The variable temperature environment tape bench with improved sensor systems is already operational at GUM and has been used by two project partners.

The UK national project 'The Light Controlled Factory' (€6.93M funding value) is taking several outputs from the LUMINAR project (the work of University College London and the University of Bath) and developing them further into a full technology demonstrator. Demonstration of the FSI system to CERN has resulted in a request from them to collaborate to develop the FSI system for their use in periodic realignment of the Large Hadron Collider and in future alignment of its successor; CERN have already purchased target spheres for the FSI system for use in alignment tasks. The *InPLanT* system has been demonstrated to a machine tool company and this has led to a request to explore further development of the technology. There has been a strong and potentially highly valuable request from a commercial organisation to enter into collaboration to develop and exploit the FSI system. There has also been an early discussion with a commercial organisation to exploit the tracking interferometer. The Capabilities and Potential report (IP Exploitation Plan) for the project outputs lists 23 items for potential commercialisation or exploitation ranging from cheap environmental loggers based on the Raspberry Pi computer, to exploitation of a developed laser tracker uncertainty mode for dynamic measurements which can be used to improve the accuracy of hand-carried laser tracker targets.

Longevity

A new collaboration between University College London and Airbus in structures testing will be using work from the project. The National Physical Laboratory has received a request from a national (UK) funding body to submit proposal for further development of the FSI system into a facility for use by aerospace companies. A plan to set up a calibration service for large coordinate measuring machines using the tracking interferometer is already underway at PTB and NPL is already continuing to improve the FSI prototype system using national funding.

Wider potential impact – meeting high-level societal needs

Assuming exploitation routes already started are successfully concluded (new LVM services at GUM, PTB, NPL are used by customers; development of INRIM, PTB, NPL outputs taken up by commercial companies; CERN takes delivery of an FSI system; UCL & UBATH outputs developed further in the Light Controlled Factory demonstrator produce eventual update), the project will have several direct impacts on many sectors:

- Instrumentation: a range of instruments will become available, giving accuracy approaching that of laser trackers but with SI traceability and ability to measure more targets simultaneously and compensate for refractive index effects. At around €100k minimum each unit, commercial instrument sales could lead to significant new EU turnover at the commercial technology partners.
- Science: the Large Hadron Collider's successor will be aligned using technology based on the project research – without accurate alignment, the largest machine ever built will not work - \$7.8 billion direct costs plus 13,000 person years of contributed effort would be wasted.
- Transport: aerospace manufacturing will be using measuring systems coming from project outputs to perform *in situ* testing of new wings without the need to pause tests to wait for measurements to be made statically; live monitoring of wing assembly jigs will lead to the accuracy improvement (400 µm down to 100 µm) required for next generation aero-structures, saving at least 100 kg in weight on each aircraft built and 122 tonnes of fuel/aircraft *p.a.*, leading to a reduction of 38.5 tonnes of CO₂ /aircraft *p.a.* and reduced overall operating costs of around €5.5k per aircraft *p.a.*
- Advanced manufacturing / Industry 4.0: factory-wide metrology system will be based at least partly on combinations of technologies from the project, enabling automated robotic assembly and manufacture at necessary accuracy level. A recent [report](#) concluded that an industrial-scale version of the Internet of Things, i.e. Industry 4.0, could add \$14.2 trillion to the world economy over the next 15 years. Advanced large scale manufacturing will require the advanced metrology from this project.

This project has produced a range of new techniques, instruments and knowledge that will enable LVM users to deliver their own advanced products, facilities, and measurement services which will all make contributions to society either by being more efficient, or generating higher impact/ new science, using fewer manufacturing resources & creating less scrap/waste, etc.

"We Shape Our Tools, and Thereafter Our Tools Shape Us"



2 Project context, rationale and objectives

2.1 Context

Large volume metrology (LVM) – the ability to measure size, location, orientation and shape of large objects, assemblies or machine tools - is a critical requirement in many high value industries where the EU is globally competitive, such as aerospace, automotive, 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 the preparation of particle beam-based therapy systems for healthcare, and in the civil engineering and surveying industries. Almost all modern large volume metrology instruments employ optical techniques in which electromagnetic beams propagate in ambient air. However, fundamental technical and environmental issues, including the difficulty of establishing traceability to primary standards of length and the determination of reliable measurement uncertainties, are preventing wider uptake of LVM or limiting the available accuracy or applicability. LVM is a process often hidden from consumers but is absolutely vital for the manufacture and alignment of many items upon which modern life and leading edge science depend. LVM is necessary because the item or items to be measured or aligned are too large to fit within conventional measuring machines or too bulky to transport to a calibration laboratory, or they are part of a semi-fixed infrastructure that cannot be removed. In other words, they have to be measured *in situ*, often in non-cooperative environments. These issues make accurate metrology very difficult to perform. The inability of the metrology to keep pace with user demand is now being acutely felt in many industries owing to commercial or regulatory pressures.

The Clean Sky Joint Technology Initiative of FP7 and the IATA Technology Roadmap have recognised that meeting targets for reduced aircraft emission require new aircraft designs, including laminar flow wings, and blended wing body architectures. Regulatory pressure behind the Initiative comes from both the Aviation Directive 2008/101/EC and from Directive 2002/30/EC concerning noise at airports.

Ubiquitous 3D metrology for ‘Smart Factories of the Future’ undertaking manufacturing and metrology-guided assembly of large structures will almost certainly use optical techniques and will therefore continue to be limited by the unavailability of 3D refractive index data. These factories will manufacture a wide range of products: consumer goods, automotive, jet engines and turbines, high speed railway trains, aircraft wings and wind turbines – not all items manufactured will be ‘large’ - the key involvement of LVM is in the factory-wide metrology network. Standardisation committees stress the industrial demand for new international guidelines for traceability, qualification and verification of inline and in-process measuring systems based on robust procedures. Yet measurement in uncontrolled environments is ignored in current standards such as ASME B89.4.19 and VDI/VDE 2617.

Fundamentally, the main metrological development of laser trackers since their invention in the 1980s is the commercial move to absolute distance meter (ADM) technology. The most significant accuracy advance was the development of the laser tracer concept, but this is a 1D measuring tool, with higher accuracy over shorter ranges - it is not directly a 3D coordinate measuring system. Furthermore, traceability of the laser tracker ADM is not easily demonstrated or checked by the user and the refractive index compensation is typically limited to a single point in the entire volume.

The lack of traceability in LVM has already been identified by the NMI community. The iMERA Length Roadmap 3, page 4 states, “*In-process metrology is a further indispensable prerequisite for real-time quality control in production. Especially for metre-range products specific advanced traceability methods have to be designed which should not be based on materialised artefacts because of their limited, size dependent stability...*” Furthermore, “*Advanced 3D measuring instruments up to 100 m*” is also named as a research target in iMERA Length Roadmap 4.

The chief scientist of a leading LVM instrument manufacturer has said “*conventional [displacement] interferometry will be dead within 5 years*”; industry is abandoning reliable fringe counting interferometry in favour of absolute distance measurement (ADM) methods that offer the user flexibility and convenience, but at the expense of measurement traceability and accuracy. Directive 2004/22/EC states within the first page that “*Correct and traceable measuring instruments can be used for a variety of measurement tasks. Those responding to reasons of public interest, public health, safety and order, protection of the environment and the consumer, of levying taxes and duties and of fair trading, which directly and indirectly affect the daily life of citizens in many ways, may require the use of legally controlled measuring instruments*”.



There is a commercial need for novel systems to bridge the gap between expensive but accurate laser trackers and cheaper but less accurate photogrammetry. This will enable a wider uptake of LVM by SMEs, leading to novel applications. Real-time feedback is a fundamental requirement for complex manufacturing applications, such as robotic drilling machines where accurate metrology over large volumes is necessary. Current large volume ubiquitous metrology networks, e.g. based on iGPS, are not sufficiently accurate and local solutions based on laser trackers are too expensive or unable to simultaneously coordinate large numbers of features within the manufacturing space.

2.2 Rationale

Thus, as shown above, LVM plays a key role in many sectors but whilst the accuracy achievable in an NMI environment has progressed significantly, at the shop floor, in uncontrolled environments, achievable accuracy has not really changed much in the last couple of decades. Despite initiatives such as NIST's 'Shop floor as NMI' program which aimed to improve the traceability links in manufacturing, the nature of the shop floor environment (metrological and financial) demands a different approach than offered in NMIs. Assumptions and simplifications in routine use in the metrology laboratory cannot be overlooked on the shop floor and this can be seen in a summary of the most critical issues affecting LVM users outside the metrology laboratory:

- Basic understanding of how a multiple-part assembly behaves under differential thermal and gravitational loading is still not very detailed. Manufacturing and assembly operations cannot take place in prohibitively expensive close-control environments, so issues such as gravitational sag, thermal expansion, uneven heating due to materials with thermal diffusivities and thermal effects on instruments/parts must be tackled using multi-disciplinary approaches involving dimensional and thermal metrology and state-of-the-art modelling.
- Erroneous refractive index compensation leads to scale errors and poor uncertainties, limiting available accuracy over ranges of more than a metre or so and thermal gradients within a large work-space induce beam bending that leads directly to coordinate errors (~0.5 mm) that cannot currently be compensated. The typical single point 'weather station' sensor that comes with a laser tracker gives a reading at only one point in the entire (large) volume – it cannot be representative of large volumetric variations in e.g. temperature.
- New Absolute Distance Meters are needed that can achieve the necessary accuracy but which are also easily traceable to the definition of the metre. Easily calibrated designs or designs which are intrinsically traceable are needed so that users can check them easily and generate meaningful uncertainty budgets. The traceability is needed critically by multi-national manufacturing organisations such as Airbus to ensure right-first-time when assembling large parts sourced from multiple countries.
- The accuracy of current metrology systems is insufficient even for existing production techniques. New manufacturing challenges will require tighter tolerances and higher quality. New metrology systems are needed to meet these new demands. When measuring critical features on large, complex assemblies, the dominant uncertainty source is often the effect of the environment. Industry has no mechanism to correct for these effects or to take the associated uncertainty contributions into account; hence conformance to design cannot be demonstrated.
- Innovation in LVM is relatively low – the work horses of the field, laser trackers, theodolites, electronic distance meters and photogrammetry systems, have been around for decades and yearly product update and launch cycles tend to focus on new software features or ease of use rather than delivering truly novel technologies or traceability.

There is plenty of scope for generating significant social, environmental and financial impact from LVM due to the high value sectors where it is used.

Aerospace manufacturing directly employs over 440,000 people in Europe and contributes around €94.5 billion p.a. to the global economy. Aviation's global economic impact (direct, indirect, induced and catalytic) is estimated at US\$ 3,560 billion, (€270 billion in Europe) equivalent to 7.5 % of world GDP and aviation transports 35 % of all international trade by value. The aerospace market is being driven by the need for fuel efficiency; shorter lead times and improved reliability. Ramp-up flexibility in aircraft manufacture is critical to achieving market-driven delivery rates (29,000 new aircraft, €2.3 trillion value, by 2030) for which a minimum 20 % reduction in lead time is required. For large, complex aircraft, this will require increased automation, which will depend on accurate in-line metrology in a large volume environment. A typical large aircraft has several hundred kg of non-designed weight (shims, filler etc.) due to imprecision in manufacturing because of accuracy losses of LVM tools in factory environments. Improved accuracy of LVM tools and better



compensation for environmental effects could lead to significant weight savings, hence lower fuel costs and emissions.

Expensive advanced **particle beam therapies** such as proton therapy will be a necessary means for healthcare provision for an EU population living longer. Better mechanical alignment through new LVM tools would allow more beam outputs from a single synchrotron source, with better accuracy of beam delivery to tumours resulting in treatments with higher cure rates.

'**Big science**', such as particle accelerator facilities rely intensively on alignment of their components. Reducing down-time by faster, more accurate LVM would help improve efficiency of these world-leading, expensive science projects, thereby reducing the burden to the tax payers within the EU. A more fundamental issue is that current LVM technology is unlikely to be accurate enough for alignment of the LHC's successor which is currently being designed.

Large components play critical roles in **energy generation**, yet often need alignment or operation in harsh conditions. Near Borkum, Germany, six gigantic windmills, with an investment value of approximately €125 million stood still for months because of gear problems which could have been prevented by better measurement before or during installation.

However, the wealth of potential usage scenarios for improved LVM is also a concern in terms of the ability of a single research project to make significant impact in just a three year period. A single project cannot tackle all the known problems and no single problem has such an overwhelming priority that requires a focus of effort so we had to achieve maximum coverage another way *i.e.* by having a broad research portfolio within a single project. Simply improving the accuracy of instruments was not enough – several new approaches were required, long-standing difficult problems experienced by LVM users had to be tackled and a balanced set of outputs had to be worked on in parallel. Through the inclusion of a range of end users in the drafting stage of the project, we were able to quickly agree a short list of necessary research objectives.

2.3 Project scientific and technical objectives

Analysis of the required research revealed four scientific objectives together with an over-arching objective to show that the project outputs are able to operate in a typical end user industrial environment. These objectives were:

- (1) To develop several new measuring tools and techniques that bridge the gap between photogrammetry and laser trackers and are capable of operation in typical industrial LVM environments, based on several different operating principles, to maximise the range of applications where they can be used, over volumes of 10 m × 10 m × 5 m with a target accuracy of 50 µm.
- (2) To develop new traceable absolute distance meters to operate over ranges of at least 20 metres, specifically a user friendly portable device and a system that will be built into a laser tracker.
- (3) To develop both line-of-sight refractive index measuring systems (one standalone and one that will be built into a laser tracker) as well as a novel network based system that can measure refractive index effects over a 3D volume. These systems will enable on-line compensation of refractive index effects in industrial environments over volumes up to of 10 m × 10 m × 5 m with a target accuracy of 1 part in 10⁷.
- (4) To undertake the necessary modelling to understand and predict how large multi-component structures (such as aircraft wing segments) behave in non-ideal measurement environments. This will be supplemented by in situ dimensional and thermal measurement data at critical points.
- (5) To verify and demonstrate the capabilities of the developed new technologies, instruments and approaches – mixing measurements at project-Partners, with those in real-world industrial environments, and demonstration of how traceable large volume metrology in industrial environments can be achieved practically.

The project was planned as multiple parallel avenues of research, with the common goals defined above, in order to target as many potential application areas as possible. The range of approaches is best summarised in a flow diagram:

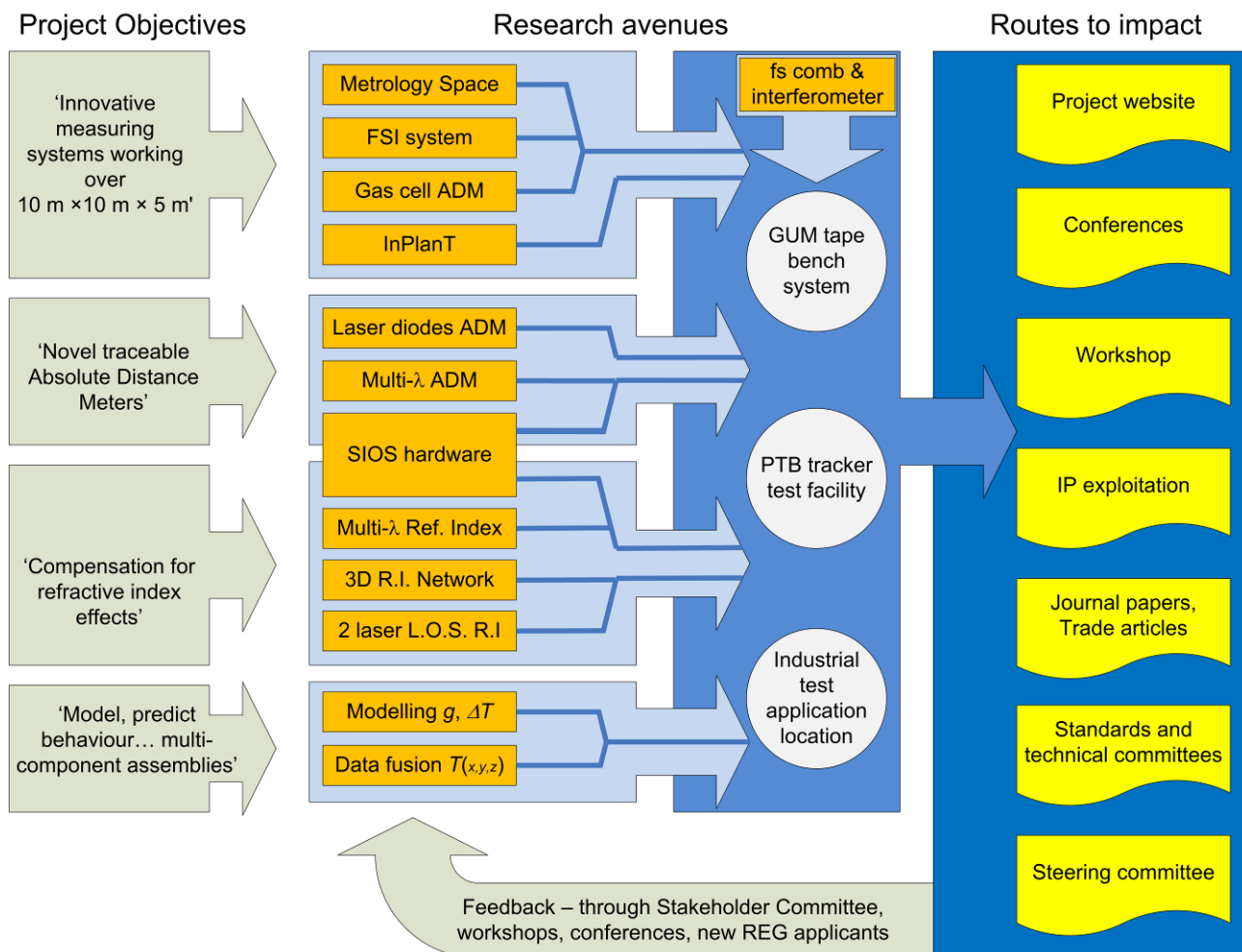


Figure 1 - Project outline. The four left side technical objectives (light blue) are the basis for the thirteen research strands (orange) which were organised as four work packages. The various strands of research were brought together in three locations (white circles) for inter-comparison and testing. Outputs from the project are collected together into the seven routes to impact on the right side (yellow flags). Involvement of external stakeholders helped steer the project and provided several channels for dissemination of project outputs.

By allowing each of the project partners to concentrate on their own area of expertise (with suitable guidance) we were able to produce many outputs in parallel at relatively high speed since no single partner could act as a bottle-neck, restricting the speed of the others. In cases where a new output was potentially on the critical path of other outputs (e.g. the new interferometer under development by GUM which would be used to test new instruments being developed by CNAM and PTB) we ensured alternatives and backups would be available as fall-back options. Similarly, the large on-site testing campaign at Airbus which was the key demonstration deliverable, was planned with additional options available (testing at PTB and at The University of Sheffield facilities). We also built in several break-points into some of the instrumentation deliverables allowing for last minute changes of plan depending on the results of early research.

The verification and demonstration objective together with the routes to initial impact were planned to occur in the very end stages of the project, when the hardware had been designed, assembled and tested though several ongoing activities were possible during all stages of the project (conferences, committee work, early research papers, etc.)



3 Research results

In summary, the research conducted by the various teams has delivered a large range of outputs which satisfy all the scientific objectives of the research project. Furthermore, the objective relating to the start of impact generation through demonstration activities has also been achieved with exploitation routes and early impact pathways already being explored.

In the sections below, the numbered outputs are those from section 1.3.

3.1 Objective 1 – innovative systems

Development of innovative measuring systems which bridge the gap between photogrammetry and laser trackers, working over volumes of 10 m × 10 m × 5 m, to a target accuracy of 50 µm.

ACHIEVED

The first objective has been achieved *via* the four systems that were developed. These systems all demonstrate novel metrology concepts and two have attracted interest from potential commercial manufacturers/adapters:

- A prototype system based on intersecting planes (*InPlanT*) which uses linear axes separated from the harsh environment. This delivered repeatability of 45 µm in an industrial on-site test campaign using short versions of two measuring axes simulating a 10 m × 10 m area.
- A prototype system similar to videogrammetry but using spherical targets and through-the-lens laser illumination. This was tested in a lab environment and achieved 100 µm accuracy over 3 m ranges.
- A system based on frequency scanning divergent beam interferometry which demonstrated an accuracy of 50 µm over small (1 m³) volumes. This system was then developed further into:
- A longer range system, again using frequency scanning interferometry (FSI), which was demonstrated at 10 m ranges in laboratory and industrial environments. Hardware failure during final testing limited the accuracy to 100 µm but earlier tests indicated that 50 µm or better will be possible.

Details of InPlanT system

The INRIM development of a proof-of-concept demonstrator of the **Intersecting Planes Technique** (*InPlanT*) is based on the idea that a point in space can be thought of as the intersection of three non-parallel planes. In particular, if the planes are orthogonal to each other, their normal unit vectors form a Cartesian coordinate system, the planes are coordinate planes, and the position of each along its normal axis is the coordinate of the plane. The coordinates of the target are then the ordered collection of the positions (x,y,z) of the intersecting planes. InPlanT is parallel, as the axes work independently of each other, each yielding a single coordinate. The actual coordinate measurements are performed at the borders of the measurement volume, where the axes are located - when the conditions of the measuring volume are harsh, the axes can experience more favourable conditions either naturally (being away from the source of the harshness) or deliberately (e.g. localised temperature control and shielding). The use of more than 3 axes can be envisaged as a route to data redundancy and either self-calibration or uncertainty reduction.

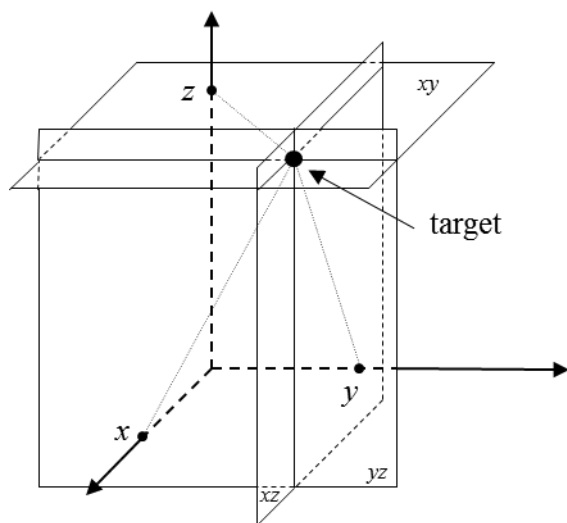
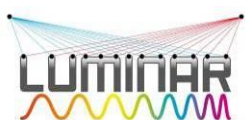


Figure 2 – InPlanT concept of coordinate planes intersecting at a target.

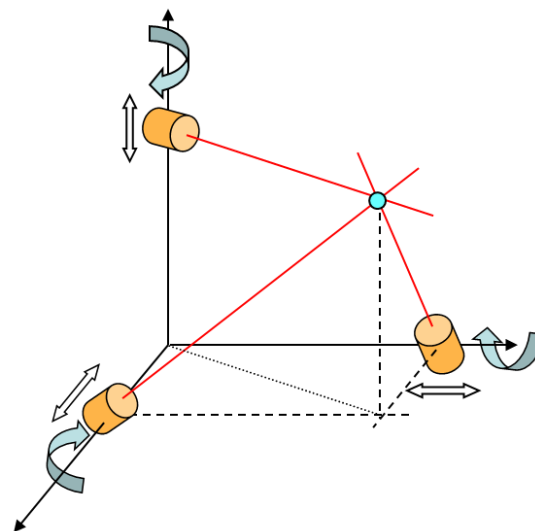


Figure 3 – Possible physical embodiment of the InPlanT system realised by three rotating pointers each moving along an independent (measured) axis.

Several designs of rotary light beam were considered: a beam source with tracking capability (like a laser tracer); a continuously tracking rotating stage; and a light blade, distributed in space (e.g. using a cylindrical lens or mirror). Preliminary tests settled on the second option of a tracking, rotating stage. This required further development in order to optimise both the beam launching and return beam detection arrangements – tests were performed using a pentaprism mounted onto a hard disk motor assembly with a four quadrant detector for the return beam. A final design was arrived at, based on a commercial linear slideway onto which is mounted a carriage with commercial rotation stage which holds the pentaprism. Light is collimated onto the prism from a nearby lens source. In order to maintain orthogonality of the planes, and to compensate for pitch and yaw errors of the linear stages an assembly of crossed autocollimators was designed and aligned. These achieved a sensitivity of 12 microradians per pixel.

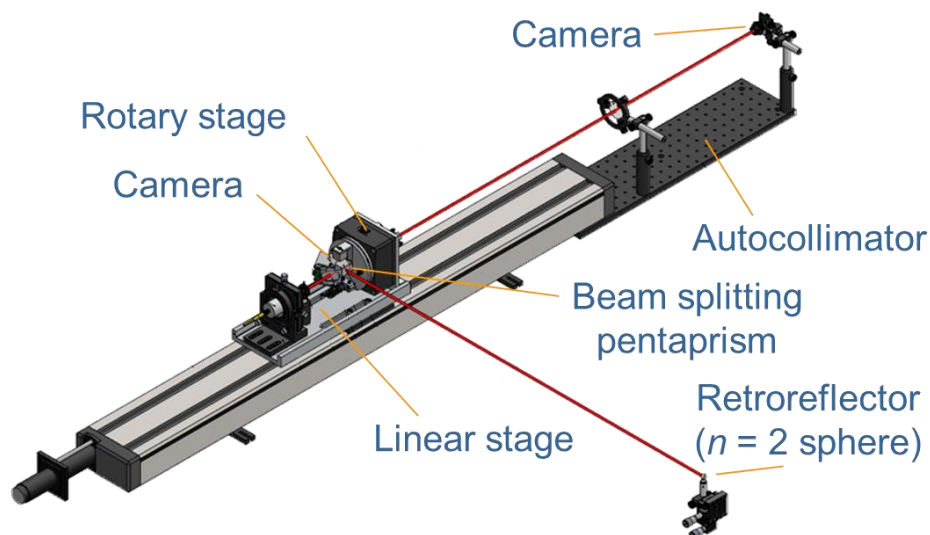
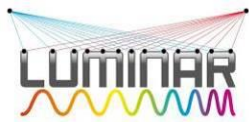


Figure 4 – InPlanT single axis – overall design.



The image in section 3.5 shows the final pair of linear axes with their rotating carriages – the project budget was only sufficient to manufacture a two-axis prototype - the key elements of the design can be easily seen. A moving linear stage carries: a rotary table with rotation axis aligned to the measurement axis, a laser collimator (fed by a fibre) aligned to the rotation axis, a pentaprism attached to the rotary table which deflects the beam 90° regardless of its orientation. The beam impinges onto a retro-reflecting target and the returning beam is deflected back by the pentaprism and impinges (through a beam splitter) onto a camera. The camera sees the (luminous) image of the retro-reflecting sphere and the position of the sphere in the camera image drives: vertically, the rotary table; horizontally, the linear stage. When the image is centred (possible residuals are compensated), the linear position is measured by a linear encoder and constitutes the sought coordinate for that axis. NPL provided the same retro-reflecting targets to INRIM as used for its FSI systems.

The mechanical and optical systems were integrated by linking the rotary stage controller to a Raspberry Pi computer using Ethernet. The Pi also linked to the camera and the linear stage controllers using USB interfaces. A web server interface was used to provide user access to the system. Testing in the laboratory at INRIM was completed very shortly before the transportation for the tests at Airbus. The pentaprism pose was adjusted on the rotary stage to obtain a residual angle of (111 ± 46) microradians. The squareness error was measured as 935 μm but was reduced down to 97 μm . The sensitivity of an axis system was demonstrated as 0.31 pixels/ μm . For these prototypes, maximum tracking speed is about 1 cm/s because of limited control bandwidth (general purpose LabVIEW setup), however the residual error is below 25 μm when target is stopped. Granularity in position due to actuator step size is similarly 25 μm . Linear position tracking noise of around 10 μm at 7 m target range was demonstrated.

In principle, to achieve a $(10 \times 10 \times 5)$ m³ measuring volume, two 10 m and one 5 m axes are required. Due to the budget limitation, the project prototype is limited to two axes only, with strokes of 1 m and 2 m, respectively. Only the 2D coordinates of the projection of the target over a measuring plane can be measured at the moment, limited to an area of (1×2) m². However, measurements in a 3D space at full distance (e.g. at 10 m) are possible thanks to the mutual independence among axes. The results obtained in a harsh environment at Airbus are detailed in section 3.5, however, in summary: an *InPlant* working prototype was constructed, limited to 2D and to a (1×2) m² area, but simulating 3D and $(10 \times 10 \times 5)$ m³ in full; the principle has been successfully validated; an error standard deviation of 45 μm was achieved in a rotary table test in harsh conditions; further test data are currently being evaluated and the system improved.

Details of videogrammetry system

One of the issues which affects photogrammetry as a metrology technique is the appearance of the targets when viewed from multiple locations and orientations. Typically targets are flat discs of reflective material (possibly with identification markers) – when viewed straight on, they appear in the image taken by the photogrammetry camera as small circular dots, however when viewed non-normally, the discs degenerate into ellipses and the flatness of the surface then contributes a measurement uncertainty. NPL's previous work on developing laser trackers using glass targets with refractive index $n = 2$ suggested that these omni-directional targets (the spheres act as omni-directional cats' eyes) could make better targets for photogrammetry. These $n = 2$ spheres have a potential downside for photogrammetry use because they reflect most of the light back towards the light source – in the case of a photogrammetry camera, the light source is usually a flash gun or ring flash mounted on the camera. In such a situation the light is reflected by the sphere back into the flash unit, rather than into the camera lens. However, by arranging for through-the-lens illumination this can be turned to an advantage as these spheres then become 'perfect' reflectors, sending light back directly into the camera lens with minimal divergence or distortion.

With assistance from UCL, NPL developed a videogrammetry camera featuring through-the-lens laser illumination together with the necessary bundle adjustment software and targets. The single camera was developed into a 3 camera 3D metrology system prototype named '*Metrology Space*'. The cameras were designed with divergent lens systems to allow a large field of view.

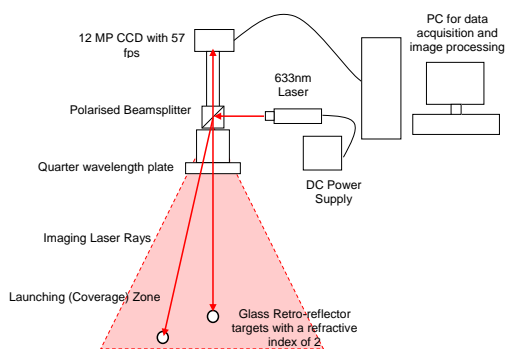


Figure 5 – *Metrology Space* camera design with through-lens laser illumination.

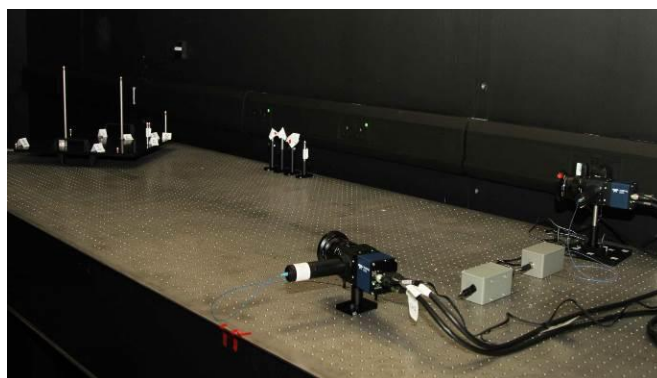


Figure 6 - Pair of *Metrology Space* cameras viewing calibration artefact.

The *Metrology Space* system was used to measure the lengths of reference bars of length 200 mm, 400 mm and 600 mm, oriented in several directions inside the 3D measuring volume of the system. The system was calibrated using a multiple-target artefact and a known length. The root mean square of the residuals was between 0.094 mm and 0.463 mm. The repeatability of the measurements (as calculated by the standard deviation of each set of measurements) was between 0.054 mm and 0.092 mm. This would indicate the system is repeatable to well within 0.1 mm, and that the reason for the relatively high measurement uncertainty and residuals are due to systematic errors rather than noise or random errors. These systematic errors are likely to be optical distortions in the imaging lenses. Nevertheless, the proof of concept of a through-the-lens laser illuminated photogrammetry system operating with $n = 2$ spheres was successfully demonstrated.

Details of divergent FSI system

Building on the successful use of $n = 2$ target spheres in the *Metrology Space* system, NPL used these as targets for a novel measuring system based on multilateration; this is the process where 3D locations of targets are determined from a set of distance measurements to those targets from a set of sensors. Given four sensors which make measurements to at least 6 targets, there are more knowns than unknowns and the system can be solved mathematically – including more targets makes gives data redundancy which allows uncertainties to be calculated. With 4 sensors and 6 targets, the solution can even be obtained if the locations of the sensors are unknown at the start (however one has to choose an arbitrary origin for the coordinate system). An added advantage of using distance measurement (compared with angle measurement of photogrammetry) is that beam bending refraction effects are considerably reduced (path directions change much more than along-the-path distance changes for the same bent path).

Distance measurements are made using frequency-scanning interferometry (FSI) which is able to measure the absolute distance between a sensor and a target. In conventional FSI, a single sensor emits a narrow collimated beam in one arm of an interferometer and, as the frequency of the laser is scanned, a series of interference fringes crosses the detector – the speed of the fringes on the detector is proportional to the distance to the target and the scanning speed of the laser (and the speed of light). To measure multiple targets simultaneously we diverge the beam with a simple lens and place the targets in the cone of diverged light (much like the visible laser cone in figure 12). However the signal at the detector is now a superposition of fringe signals, one from each target, with different periodicities based on the different target ranges. By taking the Fourier Transform of the signal, it can be shown that the targets then appear as individual peaks in the frequency domain (of the detected signal), provided they are at different distances. We simply extract the target distances from the frequency spectrum. To make the system traceable to the SI metre, we include an extra interferometer channel in which we place a hydrogen cyanide gas cell. The gas cell has absorption features well-spaced within the infra-red part of the spectrum swept through by the FSI laser (1530 nm to 1563 nm). These absorption features are quantum references which have been measured by other researchers with respect to the SI metre and are known at the 1 in 10^{-6} level of accuracy; every sweep of the FSI laser generates absolute distance measurements to all visible targets, each having in-built traceability to the metre.

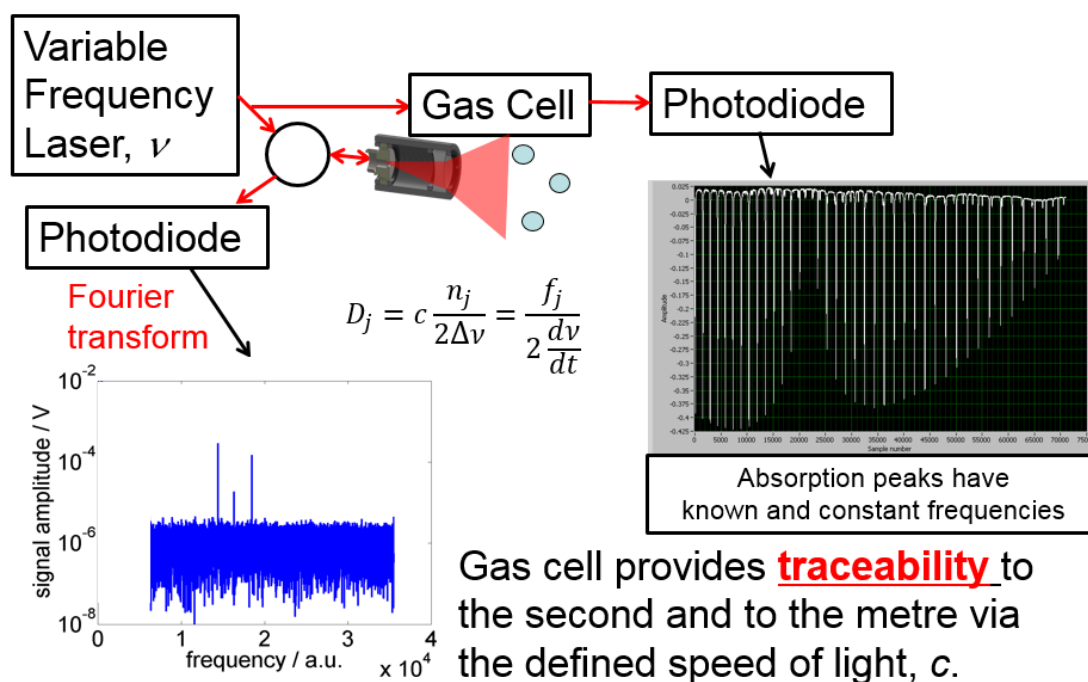


Figure 7 - Schematic representation of divergent beam FSI.

With divergent beam FSI, there is no need to track or steer beams to targets – any target in the measuring volume produces interference signals at each detector. This reduces the complexity of the sensor head design to essentially just a fibre coupler and a diverging lens, making it highly suited to mounting in industrial locations. However, when operating in an industrial environment, it is highly likely that there will be vibration present – since multi-target FSI is a frequency-based system, target motion induces Doppler-like shifts to the detected frequencies and amplifies physical vibration into a much larger error signal after FSI processing. A simple solution is to use a second FSI laser which sweeps in the opposite direction to the primary laser – in the spectrum from this laser, errors due to vibration have the opposite sign to those in the primary spectrum and taking a simple mean of the two signals removes most of the vibrational error. The disadvantage of this approach is the additional cost of an expensive FSI laser. We overcome¹ this problem by using a cheap laser and the technique of four-wave mixing in which a pump laser and a non-linear process generate a second output beam which sweeps in the opposite direction as the input beam, in perfect synchronicity; as the primary beam scans from 1530 nm to 1563 nm, the generated second beam scans from 1598 nm to 1565 nm. We process the two signals and take the mean to remove first order effects of vibration.

In tests with a target mounted on a piezoelectric actuator moving up to 0.1 mm amplitude at speeds of 100 mm/s, the individual FSI signals showed motion at the 1.3 mm level (*i.e.* 13 times the real motion) but the combined two FSI signals reduced this to the correct 0.1 mm amplitude.

Further tests were performed with targets placed within the field of view of a four sensor system (at half the 1 m maximum range, 60° cone angle). The divergent FSI system demonstrated an accuracy of 3.8 μm when using single beam FSI which was improved to 0.4 μm when using the vibration compensation.

¹ J J Martinez, M Campbell, M S Warden, E B Hughes, N Copner, A Lewis, "Dual-sweep frequency scanning interferometry using four wave mixing", *IEEE Photonics Technology Letters*, **27** (7) 733-736 (2015).



Details of multi-beam long range FSI

The sensor to reflector range of the divergent FSI system is limited by fundamental physics and we calculated² the limit based on Cramér-Rao boundary theory to be around 2 m forwards (on axis) and 0.5 m sideways (off-axis) for output powers within eye and tissue safe levels. Essentially only a very small fraction of the divergent beam hits a reflector and the reflectors only send a few percent of light back into the output fibre. There is also a signal loss before detection of the interference pattern. The elegant simplicity of divergent beam FSI is thus limited to desktop-sized volumes. To extend the range of FSI to the requirement listed in the project objectives, we employed Spatial Light Modulators (SLMs) which are diffractive optical elements which we program to form a diffraction pattern on a planar surface which takes an incoming wavefront and generates multiple output beams, one each per target. In order to know where the targets are located with respect to the SLM (and how many targets are present) we added a visible camera mounted alongside each SLM and introduced through-the-lens visible laser illumination (based on the earlier *Metrology Space* system) to each sensor head. Thus we were able to generate multiple narrow beams from the single input beam, and have each beam track a target. This significantly increased the signal to noise ratio allowing longer ranges to be achieved – in testing at Airbus, ranges over 10 m were easily demonstrated.

Control of the SLMs requires the generation of diffraction patterns using Fourier theory and to do this at speeds necessary for tracking moving targets requires significant computing power. We thus implemented the SLM control systems in CUDA³ on a graphics card in the control PC. With the longer path lengths, compensation for refractive index effects in the air became important so we developed small 'environmental loggers' based on the Raspberry Pi computer with cheap digital sensors of reasonable accuracy⁴. One logger was mounted in each FSI sensor head – the four heads were connected to the control PC using optical fibres (outputs fibre, signal return fibre), HDMI cables (for driving the SLMs), USB cables (for visual targeting camera signals) and a Wi-Fi network (for the environmental loggers). The remainder of the system (frequency scanning laser, gas cell frequency reference, four-wave mixed vibration compensation, multilateration solution software) was essentially the same as the divergent beam system.

One minor difference to divergent beam FSI is necessary due to the refraction in the optics and the change of wavelength during a frequency scan. As the laser is frequency scanned, the output beams generated by the SLMs change angular pointing direction by a small but significant amount; the effect is that of moving the directions of the beams during each scan, causing signal loss as the beam moves away from each target. We solve this by programming the SLMs to generate elongated beams ('lines') rather than narrow spots – although the direction of the beam centroid moves, only the light reflected by the target centre re-enters the detection fibre, thus the Abbe alignment criterion is preserved.

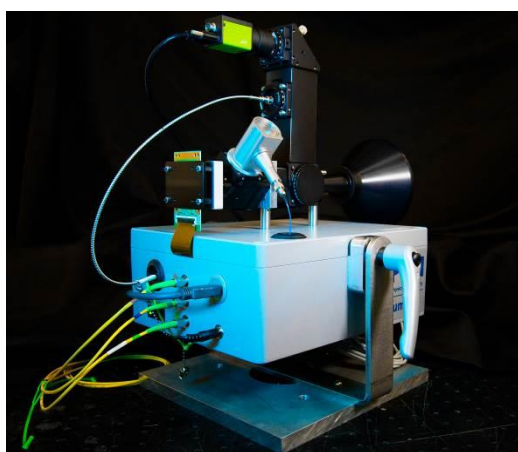


Figure 8 - Rear view of FSI sensor head showing fibre & cable connections and SLM.

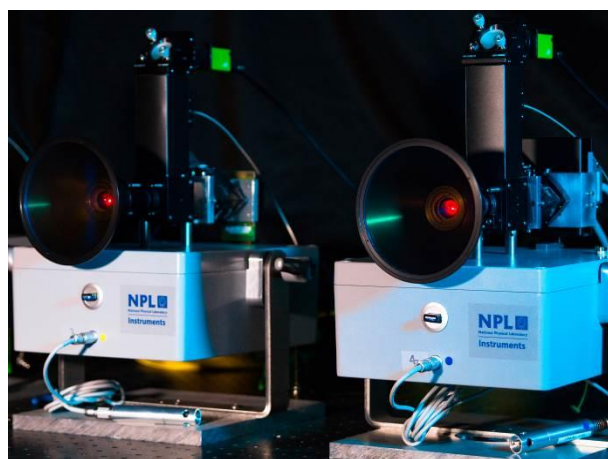


Figure 9 - Front view of 2 FSI sensors showing visible targeting laser output and wide beam aperture.

² M S Warden, "Precision of frequency scanning interferometry distance measurements in the presence of noise", *Applied Optics* **53** (25) 5800-5806 (2014).

³ CUDA is a parallel computing platform, <https://en.wikipedia.org/wiki/CUDA>.

⁴ A Lewis, M Campbell, P Stavroulakis, "Performance evaluation of a cheap, open source, digital environmental monitor based on the Raspberry Pi", *Measurement*, **87** 228-235 (2016).



The first FSI sensor head was assembled and tested at NPL and then three additional heads were manufactured immediately before the first test campaign at Airbus. The full testing of the system was thus performed during the two measurement campaigns at Airbus and PTB – for details see section 3.5, but in quick laboratory tests, the system achieved a maximum range of over 12 m, a field of view of greater than 70° cone angle and standard deviations of around 1.0 μm for a target at 2.35 m range. The system is an ideal indoor version of 'GPS': accurate, traceable, self-calibrating, able to estimate measurement uncertainty and measure multiple targets simultaneously.

3.2 Objective 2 – traceable absolute distance

Development of novel absolute distance meters which are intrinsically traceable to the SI and which operate over tens of metres range.

ACHIEVED

The second objective has been achieved *via* the two new systems that were developed together with an improved test facility:

- A portable telemeter based around cheap off-the shelf components operating at 1550 nm wavelength which could measure over ranges of 50 m with a resolution and accuracy around 2 μm , tolerant of beam break, and easy to operate.
- A tracking interferometer with absolute distance determination based on multiple wavelength interferometry, achieving absolute distance measurement with 60 μm standard deviations over a 40 m path length (in IFM mode the device operates at around 1 μm + 0.1 $\mu\text{m}/\text{m}$ uncertainty).
- The 50 m tape bench facility at GUM was upgraded with additional temperature, pressure and humidity sensors together with heating circuits, to simulate an industrial environment, to allow for testing of outputs (5) and (6) against a compensated laser interferometer.

Details of telemeter

A portable telemeter was developed during the lifetime of the project. The idea was to use relatively cheap off-the shelf components from the telecommunication industry to build an absolute distance meter with performance better than those available on the market. The principle of the instrument is very classical and is based on the measurement of the phase accumulated by an amplitude modulated light beam during its propagation in air. All optics part of the system is fibered (except for the collimation optics to the target) so that no precise optical alignment is required. A diode laser (DL) at 1550 nm is amplitude modulated by a built-in electro absorption modulator at around 5 GHz. After propagation in air the phase of this modulation is compared to the phase reference issued from the low cost frequency synthesizer used for the modulation of the DL. This frequency synthesizer is referenced to an oven controlled quartz oscillator which ensures a traceability of the measurements at 10^{-8} level.

Nevertheless, in order to take advantage of this high level of accuracy, special care has to be taken to avoid any cross-talk between the emission port and reception port, by electronic or optical means. A large engineering effort was realized in order to reduce these cross-talks down to such a level that it does not induce errors of more than 2 μm to 3 μm on the distance measurement (this corresponds to an isolation between emission and reception ports of 70 dB to 75 dB). A clear correlation between periodic errors of the instrument and cross-talk level was established. A control of this cross talk level and so of possible errors is realised before each measurement.

The typical standard deviation even over 50 m (under controlled environment) of a sample of several thousands of points, each point being integrated over 10 ms, is 2 μm . An integration time of 100 ms for each point would lead to a resolution below 1 μm .

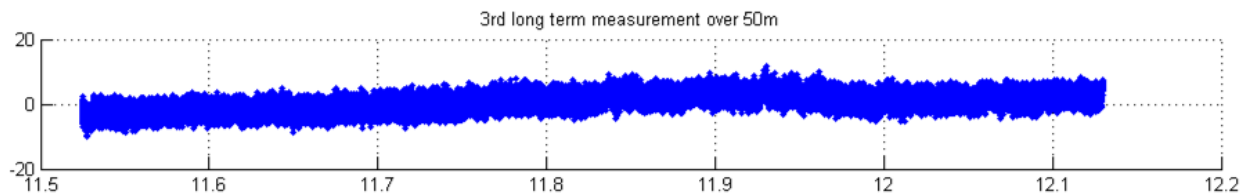


Figure 10 - Typical raw data obtained over 50 m during half an hour in a quiet environment. Each point results in an integration over 10 ms. The standard deviation of this sample is 2 μm . y axis is the measured displacement in μm and x axis is time in hours.

The accuracy of the telemeter was tested by comparison with an interferometric controlled displacement bench of 3 m. The accuracy of the reference bench was better than 1 μm thanks to a very well temperature controlled atmosphere and proper temperature, pressure and humidity measurements. The standard deviation of the difference between the reference distance and the distance measured by our telemeter was 1.6 μm over the 3 m range. So, the accuracy of the instrument is equal to its resolution, *i.e.* typically 2 μm .

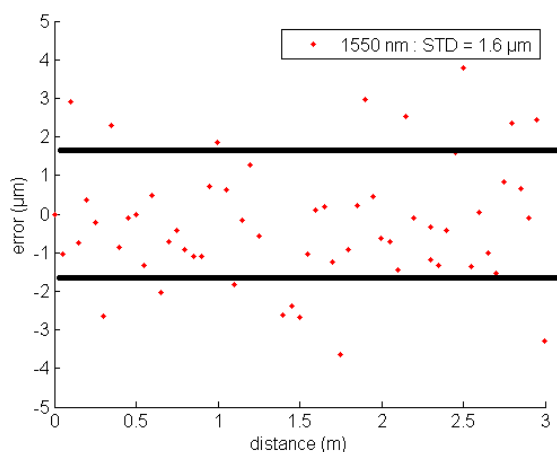


Figure 11 - Comparison between the portable LUMINAR/CNAM ADM and an interferometer over 3 m, in well controlled environment. Standard deviation of the measurement error is 2 μm .

The telemeter is not sensitive to beam break: absolute distance is realized by varying the modulation frequency and deducing the distance by a coincidence method.

The instrument is composed of an optical head of dimension very similar to a commercial laser tracker head. This optical head is linked to a laser/detection and process unit by an optical fibre and 2-3 electrical cables. A laptop is used as interface user. Work is ongoing to find a technical solution to include all optical and electronic units on the optical head. Another route for evolution of this telemeter is the use of several miniature optical heads linked to the laser/electronic unit by optical fibres, enabling sequential measurements of distance and 3D measurements.

Details of tracking interferometer

The tracking interferometer, called “3D-Lasermeter”, is based on two frequency-doubled Nd:YAG laser sources, emitting at 532 nm and 1064 nm wavelengths. One laser is stabilised on an iodine hyperfine structure transition in the visible, the second laser is stabilised on the first one with a frequency difference of 20 GHz at 1064 nm. This offers two measurement modes: using the interferometer phases of the iodine stabilised laser with fringe counting, displacements can be measured with high resolution; using the phase differences of both lasers an absolute distance measurement (ADM mode) within 7.5 mm can be measured without ambiguities, since the so called synthetic wavelengths are 7.5 mm for 532 nm and 15 mm at 1064 nm. For larger distances additional laser frequencies are generated with acousto-optic frequency shifters. The frequency shifters are also used to generate heterodyne signals for the phase detection.

The beams are coupled into polarization maintaining single mode fibres and fed into the interferometer head. The head was successfully miniaturised and adapted to a motorized mount based on the commercial



LaserTracer system from Etalon AG. Thus, the interferometer can follow a retro-reflector freely in space. Following the design idea by Hughes *et al.* [5] and Härtig and co-workers [6] the reference is fixed during this movement by replacing the reference mirror by a sphere fixed in space. The rotatable interferometer hence measures the distance between the movable retroreflector and this fixed reference sphere [1,2]. Data was acquired and processed using a 16 bit 100 MSamples/s analogue digital converter. Phase processing and fringe counting is realized using the FPGAs on the converter board.

Details of upgraded 50 m tape bench

The 50 m tape bench at GUM with limited number of environmental sensors was upgraded to allow for accurate and relatively fast measurements of refractive index of air. The measuring setup was upgraded to consist of forty air temperature sensors of type YSI 44031, five relative humidity sensors and one air pressure sensor, connected to the computer-controlled measuring system. Sensors were placed in regular intervals to cover the entire 50 m range. The tape bench is located in a measuring space with an environment which is controlled by two independent air conditioners and additional heaters in separated sections. The setup has been prepared to simulate the harsh conditions typical for an industrial production hall. All sensors were calibrated before tests for wide range of possible environmental conditions. The parameters of the characteristic has been estimated. The software for real time recording and data analysis of all parameters was developed.

Adjustment capabilities of the operating parameters of two independent air conditioners were used to obtain large gradients along the test bench or rapid changes in local conditions. The air conditioners located at both ends of the 50 m tape bench were tested in different variants of work to achieve required conditions. Combinations of cooling, heating and normal state were examined. During preliminary tests the air temperature gradient on the level of 4 °C and relative humidity gradient on the level of 11 %RH for distance of 50 m were achieved. The highest gradient of temperature was achieved with use of additional convection heaters. The vertical gradients perpendicular to the bench axis were also examined.

The uncertainty of the measuring system was estimated using a Monte Carlo method. Several series of collected raw data sets were used together with thousands of randomly generated measurements for each of series. Correlation between amplitude of changes of temperature and humidity was observed. This fact was used to estimate the uncertainty of mean humidity calculation. Differences between n values calculated using raw and randomly generated data was used to estimate the uncertainty of the system. The estimated uncertainty is $U(n) = 4.2 \times 10^{-7}$. This level of uncertainty was required for the verification of the CNAM and PTB measuring systems during the measurement campaign at GUM, which took place before the end of the project.

3.3 Objective 3 – refractive index detection & compensation

Development of a method to provide on-line compensation for refractive index effects in ambient air in industrial environments, targeting 10^{-7} accuracy over a volume of approximately 10 m × 10 m × 5 m.

ACHIEVED

The third objective has been achieved *via* three approaches that were successfully developed:

- The portable telemeter was fitted with a second wavelength at 785 nm which enabled it to achieve 500 µm accuracy in refractive index compensated distance measurement at 50 m range.

⁵ E. B. Hughes, A. Wilson, and G. N. Peggs, "Design of a high-accuracy CMM based on multi-lateration techniques," *CIRP Annals - Manufacturing Technology* **49**, 391 – 394 (2000).

⁶ F. Härtig, C. Keck, K. Kniel, H. Schwenke, F. Wäldele, and K. Wendt, "Tracking laser interferometer for coordinate metrology," *Technisches Messen* **71**, 227–232 (2004).



- The tracking interferometer had an additional set of wavelengths added and, despite some optical problems, demonstrated agreement with conventional refractive index measurement to within 5×10^{-7} .
- A range of photogrammetry tools (multi-spectral imaging, digital axicon camera, MathCad refraction analysis, volumetric refractive bundle adjustment software) were developed and combined into a system which can perform photogrammetric analysis of images with refraction modelling and signal environmental instability across large volume manufacturing spaces.

Details of compensated telemeter

An air index compensated version of the LUMINAR/CNAM telemeter described above was developed. An additional wavelength was implemented in the telemeter. The principle of the measurement was to realize a distance measurement simultaneously with a second extra wavelength (785 nm) and take advantage of the knowledge of the air index dispersion between 1550 nm and 785 nm. If both measurements are realized with a high accuracy, the difference of the phase accumulated by both beams is used to correct the measurement done at one of the wavelength from air index effect. The true value of distance is given by:

$$D = D_1 + A (D_2 - D_1),$$

where D is the compensated distance, D_i the distances measured at λ_i taking air index equal to unit, and A is a factor which numerical value is depending on both wavelength and is given by air index dispersion equation (equal to 50 for 1550 nm and 785 nm). This A factor acts as an amplification factor of the measured difference of distance $D_1 - D_2$. In order to get a given uncertainty on the air index compensated distance, measurements at both wavelength should be realized with an uncertainty A times better.

The second telemeter at 785 nm was based on the same principle as the telemeter at 1550 nm briefly described above. A compact measurement head was realized including both wavelength, enabling an easy alignment of both optical beams on the measurement path and a robust operation. Nevertheless, essentially due to the optical amplification principle used (based on a semiconductor amplifier) this second telemeter had lower performance than the 1550 nm telemeter. For this reason it was not possible to reach uncertainty on the compensated distance as low as could be expected by excellent performances at 1550 nm. Compensation at the scale of 500 μm was obtained. Great improvement is expected in the future by changing both wavelengths to reduce the A factor and realize two telemeters with the same good performance.

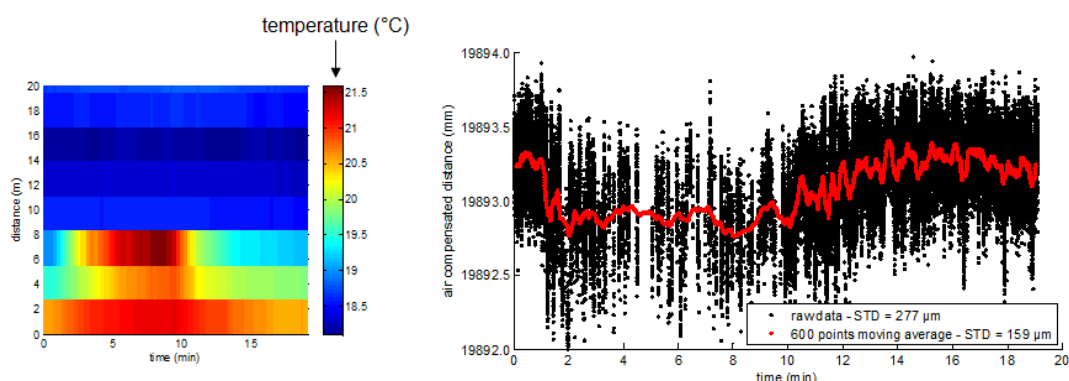


Figure 12 - Distance measurement over 20 m without temperature and air pressure measurement, using air index compensation formula. Distance was measured simultaneously at both wavelength (1550 nm and 785 nm).

Details of compensated tracking interferometer

The 3D-Lasermeter uses frequency doubled Nd:YAG lasers which offer both frequencies in the infrared (1064 nm) and visible (532 nm) at the output ports. An interferometer measures the optical path length in air, which is different for separate wavelengths due to dispersion. From both optical path lengths for 1064 nm and 532 nm the mechanical distance can be calculated. For dry air, no temperature, humidity, and pressure sensors are required. With humidity, only the partial pressure of water vapour in air has to be measured, e.g. by a hygrometer. The challenge of this measurement is the fact that uncertainties in the difference of the measured optical path lengths are scaled by a large factor. In fringe counting mode the phase refractive index



of air has to be used, giving a factor of ~ 65 . When measuring with the synthetic wavelengths in absolute distance mode, the group refractive index has to be used and the factor is smaller (~ 22.5), but an additional uncertainty scaling by the ratio of the synthetic wavelength (7.5/15 mm) to the optical wavelength (532/1064 nm) of $\sim 14\,000$ is present, giving a total uncertainty enlargement of about 300 000.

The experimental performance of the fringe counting mode was very satisfactory, for 1D measurement a constant uncertainty of $0.9\ \mu\text{m}$ and a length dependent part of 1×10^{-7} / was demonstrated in controlled environment against a conventional He-Ne counting interferometer. In harsh environment with temperature gradients of up to 10 K in the beam path, a reference interferometer could not be used. The 3D-Lasermeter, was capable of monitoring a fixed target continuously in most cases, and compensation worked successfully. In an industrial environment, in comparison with a sophisticated sensor network, deviations of 5×10^{-7} between the Lasermeter and the environmental sensors were observed. This can be well explained by the distribution of the temperature sensors. For 3D measurements with tracking of the reflector additional length independent uncertainty contributions occur, giving a constant part from $1.3\ \mu\text{m}$ in controlled environment to estimated $4\ \mu\text{m}$ in harsh conditions.

The absolute distance mode suffered from polarisation instabilities in the beam splitters. Broadband beam splitter plates, which cover both wavelengths, turned out to be not useful and broadband non-polarising beam splitter cubes were not available for the wavelengths 532 nm and 1064 nm. As a compromise beam splitter cubes for the visible spectral range were used. Probably thermal- and stress-induced birefringence lead to small drifts in the measured lengths. The large uncertainty scaling factor of about 300 000 led to a standard deviation of $60\ \mu\text{m}$ for the refractive index compensated result at 10 s integration time on a 40 m path in an air conditioned lab. This length independent scatter corresponds to a standard deviation of merely $0.2\ \text{nm}$ ($60\ \mu\text{m}/300\,000$) in the difference of the measured lengths for the four optical wavelengths used. In harsh environment however, the drifts were much larger. Hence, the refractivity-compensating absolute measurement mode could not be implemented with satisfactory uncertainty measurement performance in the 3D-Lasermeter. The refractivity-compensating counting measurement mode, showed a convincing performance and can be used, e.g., for multilateration-based calibration measurement in uncontrolled environments.

Details of photogrammetry-based techniques

UCL's contribution was based around several approaches, all based on photogrammetry – the observation of multiple targets in multiple camera images and correlation of the targets (together with a calibrated linear scale) to determine 3D coordinates. The focus of the research was the detection of (and possible compensation for) refraction effects which bend light beams causing errors in computed 3D coordinates. Because photogrammetry is a volume-intensive measuring system, deploying a network of multiple simultaneous optical sight lines across a factory space, it has the potential to provide refraction signalling information to other narrower beam systems (such as laser trackers) operating in the same 3D volume. The three focuses were: use of multi-spectral imaging; volumetric refraction modelling; and development of a digital pseudo-axicon camera.

The first development from UCL was to develop a refraction simulation based on William's differential bending formulation (which is more applicable than the more basic Snell's law). The working space, through which the measurement rays pass, is divided into cuboidal voxels. Readings from 8 thermocouples at the voxel corners, are used to interpolate the temperature T at the position of the current ray segment. To interpolate temperature at a point inside the voxel, trilinear interpolation from the 8 corners is used. The interpolated temperature gives the refractive index n using Bönsch and Potulski's formula. From this formula the gradient of n w.r.t. T is calculated and from the interpolation equation for T , the vector gradient of T with respect to the 3D space is calculated.

A first implementation of the system was based around the use of multiple cameras (with differing focal length lenses and optical qualities) coupled with targets consisting of LEDs operating at a range of wavelengths (*i.e.* an implementation of the multi-spectral imaging designed to detect wavelength-dependent dispersion). Initial tests of the proposed system at NPL against a laser tracker proved inconclusive as they were performed in a relatively small laboratory where thermal effects on the mounting structures dominated. After further development of the theory and refinement of the hardware to use long focus lenses, a new test (not in the original plan) was performed using the 50 m tape bench at GUM in June 2015. Four clusters of LED targets (violet, blue, green, yellow, red, IR1, IR2) were positioned in a vertical pattern 50 m from a typical



photogrammetry camera and imaged with a 150 mm telephoto lens capable of detecting angular change to better than 1 arc second. Using a mix of heaters and air conditioning, 14 different temperature states were created. These were sensed with an array of 29 thermistor-based temperature sensors arranged in a wedge-shaped pattern which conformed to the camera's field of view. The test was simulated in MathCAD but agreement between test and simulation was imperfect and improvements were needed.



Figure 13 (left) Multi-spectral targets in use in the 50 m GUM tape bench location.

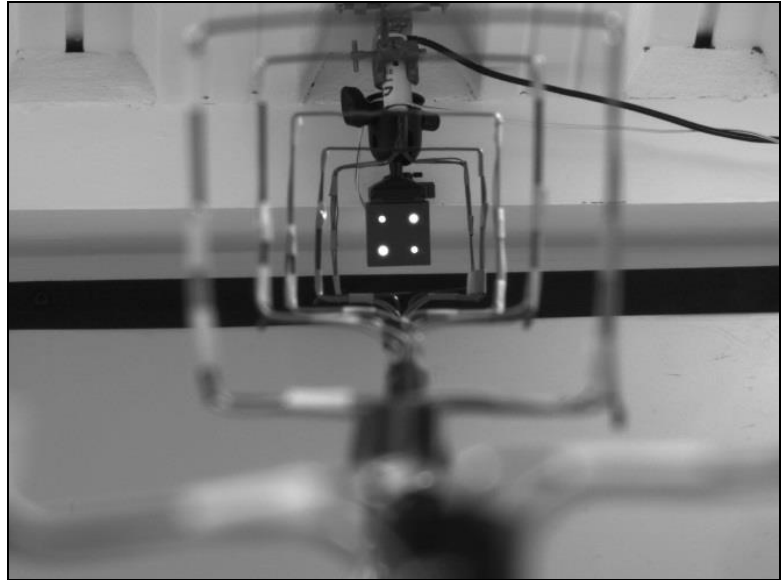


Figure 13 (right) View of a co-axial IR/violet quadrature target along sensor quad 'tunnel' using a long focus 150 mm lens

After the early stage testing, the modelled theory was integrated into UCL's own photogrammetry analysis software *Vision Metrology System* (VMS) this is a photogrammetric processing package developed by Stuart Robson and Mark Shortis. The new software implementation allows simulation of multiple cameras imaging a multi-target array. The software calculates target image locations with and without refraction based on an input array of 3D target location estimates and a factory space temperature profile. From these data refracted and un-refracted image observations can be simulated for each image in the photogrammetric network.

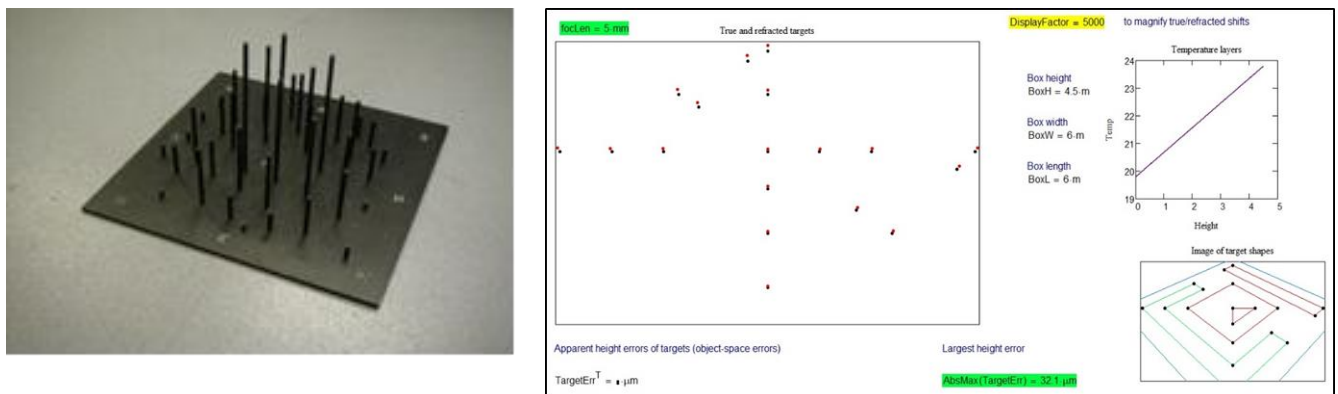


Figure 14 – A frame from a 20x scaled-up version of UCL's 8-camera test rig viewing a scaled-up 'Manhattan' target array (left) through a 0 – 50°C vertical, linear temperature change.

These simulated data allow estimation of how the photogrammetric bundle adjustment is affected by refraction present in the environment. Next, adjustment with control points defining the datum, e.g. the surrounding base points of our target array, results in the network adjustment changing the camera positions and orientations to give a best fit to the control. Agreement to control is better than 0.1mm. A new solution with an alternative datum defined by the positions and orientations of the photogrammetric cameras then gives coordinate deflections that are in agreement with the 0.3 mm – 0.5 mm predicted vertical deflections due to thermal gradients. The final test of the technique was performed at Airbus (see section 3.5) and initial analysis of the



data suggests that the refraction effect is only just detectable using the combination of telephoto lens and multi-spectral imaging.

In the practical implementation of the technique the cameras acquire an imaging network and run a bundle adjustment as if no refraction were present. The software then simulates a measurement configuration with refraction and random image measurement error from a standard network approach and a set of localised temperature measurements. UCL then analyse the simulated measurements with VMS assuming no refraction error. The refraction errors are then expected to get absorbed by the least-squares adjustment but the camera/object configuration probably won't be a lot different from the true configuration. Next, UCL use this approximate geometry, and object-space temperatures, to calculate errors for all individual pointings which are due to refraction. Finally, the software is used to apply the refraction corrections to the image measurements and re-calculate the network with VMS. This process allows UCL to understand what can be determined with a given image geometry and measurement uncertainty. They then iterate the solution as required whilst checking the magnitude of image measurement residuals within the process.

The third research avenue explored by UCL was the development of a pseudo-axicon digital camera. The new sensor was based on the CENTRAX camera (basic design is a monocentric lens with hemispherical elements) which was developed at NPL in 1980s to obtained axicon images on film. The camera was donated by NPL to UCL and the research team have since fitted the lens (via a custom designed mount) with a digital uEye monochrome camera. The new digital Centrax camera was then characterised with UCL's 'Manhattan' target array object, which was illuminated by LED ring lighting, at 3 wavelengths. Initial analysis from the testing shows extremely low lens distortion in the VMS analysis. Further development of this camera/lens combination should provide increased precision at detecting dispersion effects, however that development will be outside the scope of the LUMINAR project.

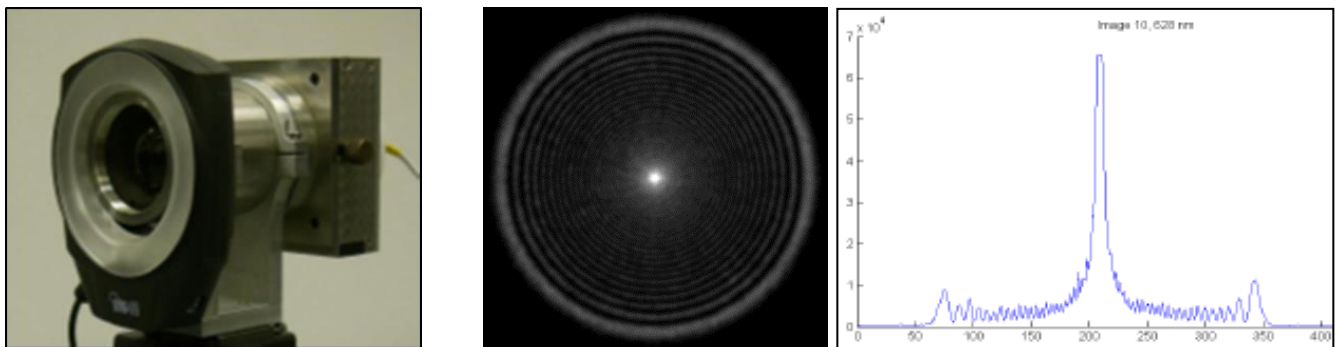


Figure 15 – UCL's Digital Centrax camera, an axicon target image made with the camera using a LED target and a cross section across the target image.

A final element of the UCL work is the initial design of the 3DIMPact website at UCL. This is planned to become a detailed online knowledge base of portable 3D metrology, and related technologies, and is being developed by UCL's 3DIMPact group with partners Dutch publisher Geomares and Brazilian research institute, SENAI Metal Mechanics. Outputs from the LUMINAR project are destined for inclusion in this web resource. The UCL research started within the LUMINAR project is being continued further under a nationally-funded project, The Light Controlled Factory, together with UBATH and NPL. The LUMINAR project was used to develop the initial concepts which are being taken further in the follow-on project.

3.4 Objective 4 – thermal compensation

Modelling, understanding and predicting the behaviour of multi-component assemblies (up to 5 m dimension) in non-ideal environments (5 °C temperature deviation). LVM has to work in situ in factory environments where the temperature is uncontrolled and not at the standard value of 20 °C.

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The fourth objective has been achieved *via* two key outputs:



- A hybrid thermal compensation scheme was developed and implemented. In this scheme data from a sub-set of dimensional measurements is fed back into a finite element model analysis together with temperature data, to iteratively improve the accuracy of the FEA simulation. The model can then be used to perform thermal compensation of the entire assembly/structure.
- A test component/assembly, typical to aerospace manufacturing, was designed instrumented and used as a first stage test of the hybrid technique in a laboratory environment. The technique achieved an accuracy better than linear expansion theory and better than single probe-compensated laser tracker measurements.

Details of thermal expansion research

Thermal expansion in large volume metrology is often the largest source of uncertainty as the environments are highly variable. In situations where temperature control is not practical or economical, a method needed to be created to compensate for these effects. Aerospace assembly, integration and test (AIT) environments can be challenging from a thermal expansion perspective. Demanding product specifications further compound this effect.

Through a combination of expanded temperature measurement and established simulation techniques, the Hybrid Metrology approach was born. This approach is depicted in the flow diagram in Figure 14. Finite element analysis (FEA) has been used in the design phase of manufacturing for a number of decades in order to provide design verification and test products in typical application conditions. The thermal expansion problem is commonly considered in FEA and bringing this into the operational stages of manufacturing as part of the inspection process seemed to present an opportunity to improve upon traditional uniform scaling.

Nominal CAD models are imported into the FEA environment. Temperatures around the structure to be measured are logged and applied to the FEA model as boundary conditions. The FEA simulation can then produce a list of predicted displacements from the standard temperature of 20 °C. Validation experiments of the FEA simulation can be carried out to assess how well the model is predicting the real-world measured displacement.

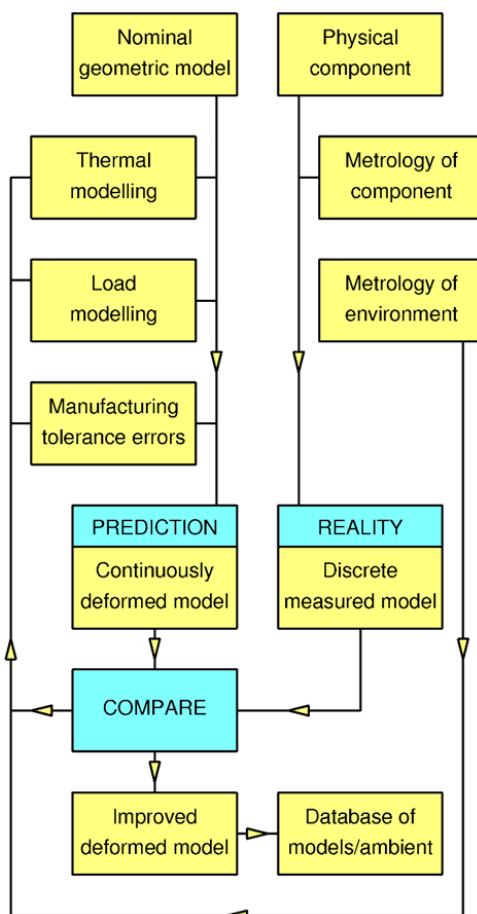


Figure 14 - Flow diagram depicting the Hybrid Metrology approach.

At the outset, the development of the method required that a digital CAD model of an aerospace structure was available, which was provided by Airbus. This put into perspective the complexity of the challenge but also informed the planning of how the experimental activity should progress.

Initial FEA modelling of simple test cases was carried out and compared against theoretical calculations. This modelling then progressed to carrying out some basic convergence and sensitivity studies before embarking on experimental studies.

Description of research on multi-component assembly

An assembly was designed and manufactured to represent a laboratory-scale aerospace structure.

The cylindrical assembly stood around 1.8 metres high and consisted of 4 equally proportioned 'barrel sections' that could be assembled on top of each other. Each barrel section is formed of two circular flange plates separated by 4 supports. Each support is made up of two perpendicular sections in a T-shaped configuration or 'T-sections'.

Aluminium alloys are commonly used aerospace materials that also exhibit a relatively high coefficient of thermal expansion (CTE). Greater thermal expansion was desirable in order to separate thermal expansion effects from the uncertainty of the dimensional measurement instrumentation.

Experiments on the assembly were carried out to establish how well the simulation could predict the thermal expansion in all directions. In order to show the benefit of using an FEA-based approach, a challenging scenario was devised in which heating of the structure was asymmetric as can be seen in Figure 15. Cases in which heating is non-uniform and/or asymmetric produce deformations that cannot be corrected using linear CTE alone.

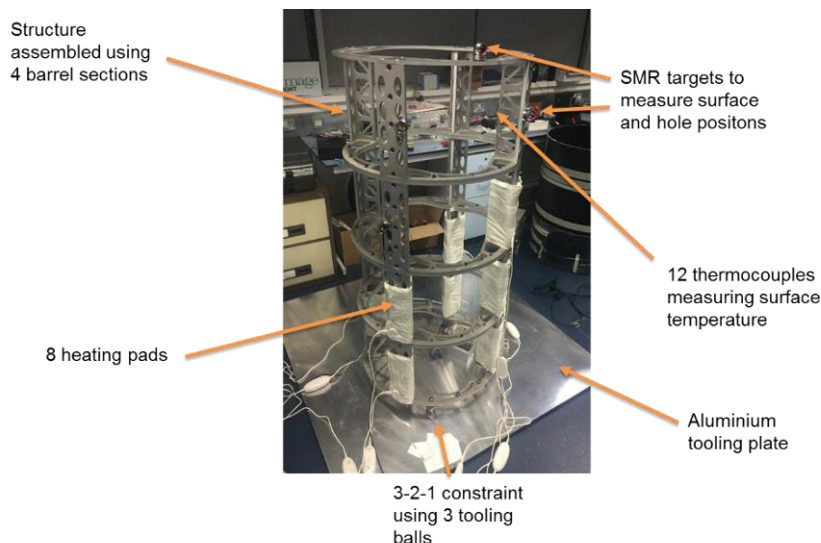


Figure 15 - Photograph of the experimental assembly setup.

Heating was achieved through the use of heating pads wrapped around the T-sections. The assembly was covered with 12 surface temperature sensors, with 1 measuring the ambient temperature. Dimensional measurement was performed using the laser tracker and drift nests were fixed to the structure at the top and base to measure displacements. Dimensional and temperature measurements were taken periodically before, during and after heating.

Using the temperature measurements from the experiment as boundary conditions, the FEA simulation was found to be able to predict thermal expansion at each point more accurately than traditional linear CTE based methods. It was also found that using a transient temperature distribution using selected data from different time points in the heating process produced a more accurate final temperature distribution than the final heated temperature measurements alone as shown in Figure 16. This experiment formed the basis of a live demonstration at the University of Bath where each stage of the process could be observed. Learnings from this assembly study are currently being used and progressed in the EPSRC-funded *Light Controlled Factory* project, where the same assembly artefact will be corrected to enable a robotic machining operation.

	X (μm)	Y (μm)	Z (μm)
Measurement	-122	-123	265
Simulation	-83	-79	243
Δ	39	44	22

Traditional Linear Scaling			359
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Figure 16 - Results from the demonstration showing how the simulation and traditional scaling compare to the actual heated measured values.

In December 2015, following the demonstration, a structure was selected at an Airbus wing-bending test facility that could be used to test the method at a far larger scale in March 2016. Temperature data was captured over the course of the measurement campaign, alongside dimensional laser tracker data from the structure shown in Figure 17. CAD data was supplied by Airbus and had to be remodelled to be used more efficiently in FEA. Comparing the temperature data to the total displacement from around the structure show that thermal expansion has a significant impact on large scale steel structures. Further work is again being done in the Light Controlled Factory project on the modelling of this large structure to improve the simulation predictions and to optimise computational efficiency.



Figure 17 - Collection of photographs from the Airbus measurement campaign showing the laser tracker (top-left), spherically mounted retroreflector (SMR) on structure with drift nest (bottom-left), and the test rig structure with researcher (right).

3.5 Objective 5 – testing and demonstration

Verification and demonstration of the capabilities of the developed new technologies, instruments and approaches – mixing measurements at project-Partners, with those in real-world industrial environments, and demonstration of how traceable large volume metrology in industrial environments can be achieved practically.

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The fifth objective has been achieved *via* three measurement campaigns:

- An inter-comparison of outputs (5) and (6) was performed at project-Partner GUM using their new facility (7). This allowed verification of the ultimate accuracy of these new instruments.
- Output (4) was taken to project-Partner PTB and tested in their Reference Wall facility, allowing a test of the technique's ultimate accuracy in a good environment.
- Industrial testing/demonstration of outputs (1), (4), (5), (6), (8), (9) & (10) took place at Airbus, Filton, UK in a live factory environment. This included measurements on a 45 m long diagonal path across the side of the building (maximum range available indoors) and on the 12 m high wing test rig. All 7 project outputs which were taken to Airbus were able to make satisfactory measurements in this location where there were temperature gradients, vibration and acoustic noise present.

Description of the campaign at GUM

GUM upgraded their 50 m interferometric bench to be able to simulate an air index gradient along the propagation of an optical beam. Furthermore, this gradient can be modified with time: this gradient is continuously measured but not controlled. Several heaters located in isolated boxes were set up along the bench to simulate strong turbulence while air conditioning conditions of the whole room can be changed. From 2016-02-15 to 2016-02-19 CNAM and PTB visited GUM with their respective devices in order to be tested on this 50 m bench.

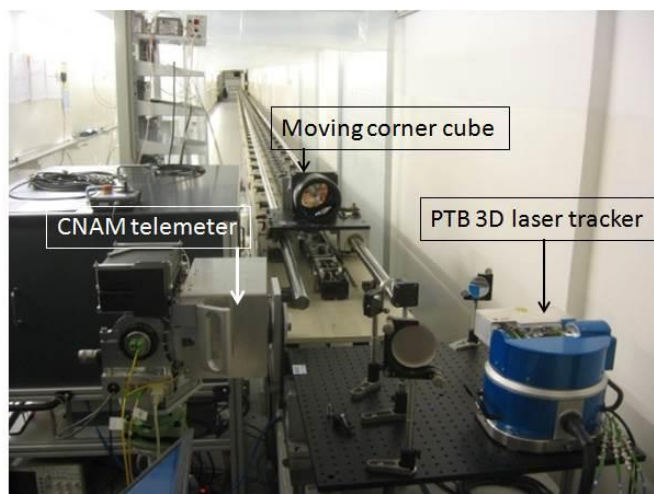


Figure 18 - View of the 50 m long GUM bench with PTB and CNAM devices aligned for measurements.

The PTB 3D-Lasermeter was aligned to the bench, in parallel to CNAM's Telemeter. Mainly two types of measurements were performed: measuring lengths up to 50 m in fixed intervals in nearly stable environment and measurements at a fixed position with variations of the refractive index of air either by the heaters in the boxes (strong turbulences) or by the air conditioning system (temperature gradients).

Measurements were first realized over 50 m on stable environmental conditions with the CNAM system. No scale error was detected on this telemeter over 50 m. The absolute distance mode is robust and never failed during the campaign whatever the distance measured. Nevertheless, due to technical issues on the second wavelength (785 nm) it was not possible to obtain an air index compensation better than 500 μm , as already mentioned in section 3.3. Significant improvements are expected by changing of technical option for the second wavelength.

The PTB 3D-Lasermeter was successfully used to perform measurements of a fixed length in fringe counting mode. The 3D-Lasermeter was thus capable to monitor at fixed position with turbulences in the beam path over time successfully. During a heating and cooling phase the refractive index compensated length for a 19 m path stayed constant in contrast to the length compensated using environmental data acquired by a sensor network. Using the latter conventional compensation approach, the measured optical path lengths showed length changes of up to 30 μm during heating while the mechanical path remained fixed. In case of the intrinsic refractivity-compensation, only the noise level of the refractive index compensated length increased during the turbulences. This important measurement result is summarized in figure 19.

As mentioned in chapter 3.3, the absolute distance measurement mode worked unsatisfactorily for the distances up to 50 m, with an uncertainty for the refractivity-compensated result of 0.5 mm for 10 s integration time.

The verification experiments with the fixed length could be performed in fringe counting mode. The 3D-Lasermeter was thus capable of monitoring a fixed position with turbulences in the beam path over time successfully.

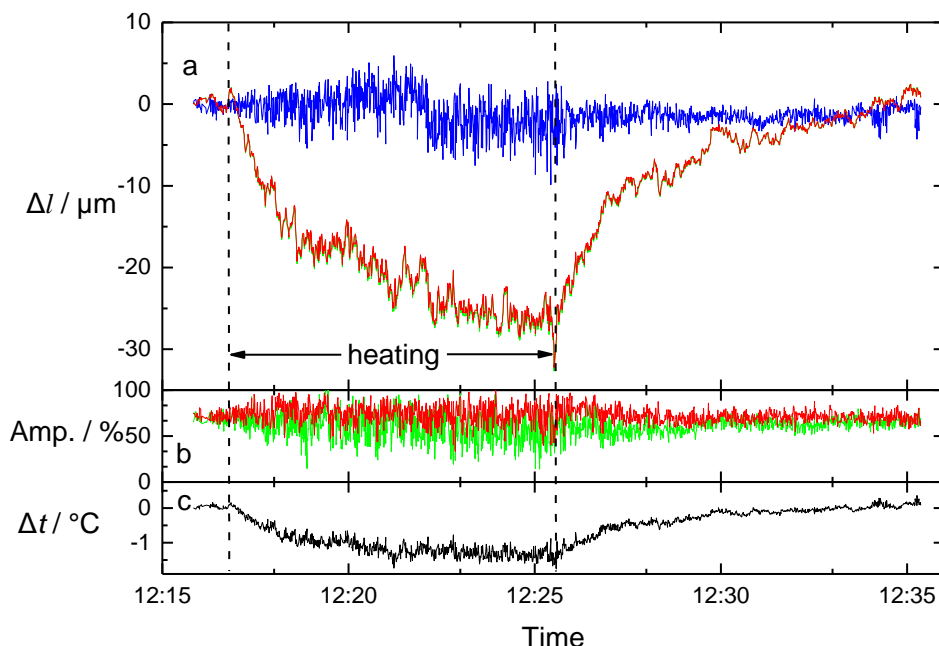


Figure 19 - Result of a measurement over a fixed 19 m path with heating of a part of the beam. (a) length change Δl of the refractive index compensated result (blue) compared with the result calculated with air index from sensor data (green and red), (b) signal amplitudes for 532 nm (green) and 1064 nm (red). (c) temperature difference between mean sensor temperature and temperature derived from dispersion. Picture taken from [7].

In addition to the contractual requirements, GUM offered the use of their tape bench facility to UCL for testing of their long range multi-spectral photogrammetry system in June 2015. Four clusters of LED targets (violet, blue, green, yellow, red, IR1, IR2) were positioned in a vertical pattern 50 m from the camera and imaged with a 150 mm telephoto lens. Using a mix of heaters and air conditioning, 14 different temperature states were created. These were sensed with an array of 29 thermistor-based temperature sensors arranged in a wedge-shaped pattern which conformed to the camera's field of view. The test was simulated in MathCAD but agreement between test and simulation was imperfect and improvements had to be developed before implementing the test system at Airbus later in the project. The testing at GUM was thus very useful for the UCL research.

Description of the campaign at PTB

Although this campaign was originally planned to occur earlier in the project (*i.e.* before the Airbus campaign) several items of hardware (including one laser) had been delayed from the suppliers so this campaign was held back as late as possible (in fact to the week immediately before the final project workshop) to allow for final hardware delivery. In the week of 9-13 May 2016, NPL took its long range FSI system to PTB, Germany in order to use the PTB Reference Wall facility – this unique large environment allowed testing of the FSI system at full range in an environment where it could demonstrate its best measurement capability. The measurement campaign had to be delayed by one day due to a laser being damaged during transportation and the laser used for vibration compensation had still not been delivered to NPL, so this part of the system was not operable. Nevertheless, with the assistance of PTB, NPL was able to set up a network of 4 FSI measuring heads and a selection of 15 targets, incorporating the long carbon-fibre spans of the PTB facility. Although the PTB facility does not have active temperature control, the large volume has a rather stable temperature and solid floor and walls, so is quite stable. Reference locations of the targets were determined using a laser tracker.

⁷ Meiners-Hagen K, Meyer T, Prellinger G, Pöschel W, Dontsov D, Pollinger F, "Overcoming the refractivity limit in manufacturing environment", accepted by *Optics Express*.



The test scenario covered a 10 m × 5 m × 2.5 m measurement volume, included 4 sensor heads and 15 targets, with the targets all measured simultaneously thus demonstrating the capability to split the FSI beam into at least 15 beams, one per target. The geometry of the system resulted in a maximum distance between a sensor and a target of 8.328 m and a minimum distance of 3.240 m. The FSI heads were operated with an angular field of view of 70°. The processing of the data using the multilateration software identified and located all the targets and predicted measurement uncertainties of around 100 µm in the x and y coordinates and around 300 µm in the z (vertical) coordinate. The comparatively larger vertical uncertainty is due to the limited vertical spread (2.5 m) of the FSI sensor heads due to limited mounting locations. Comparing the FSI results with those obtained using the laser tracker (pointing at one target at a time) showed a difference with tracker measured positions of around 50 µm – 150 µm, *i.e.* within the uncertainty estimated by the multilateration solution.



Figure 20 - NPL's FSI system in use at the PTB Reference Wall facility.

The results are very good when taking into account several factors which NPL did not have time to solve fully before travelling to PTB:

- there was no vibration compensation available (pump laser had been on order for 4 months but had not been delivered);
- to maximise power from the stand-by FSI laser (the main laser was damaged in transit) we had to use spot projection, not line projection (the wavelength change during a frequency sweep causes spot movement and projection of a line pattern can help but is more difficult to arrange in short time);
- no optical distortion correction was implemented to compensate for the geometric optical distortion known to be present in the FSI beam projection optics;
- poor geometry / redundancy of the target locations (a common occurrence in LVM) meant that the z axis was poorly controlled in the network.

Overall, we showed the FSI concept to work as well as predicted by the multilateration theory, as well as achieving the goals for an industrially relevant system which had been demonstrated in the campaign at Airbus (see next section). Only the final ultimate achievable accuracy was not demonstrated due to hardware failures and lack of time. This will be progress after the project.



Description of the campaign at Airbus

The most ambitious part of the project was to plan a multi-partner measurement campaign at an industrial location; however this was a key part of the project and was achieved on the planned date. The new measuring systems from CNAM, INRIM, NPL, PTB, UCL and University of Bath were taken to Airbus, Filton, UK for a two week period of simultaneous measurements, from 2016-02-29 to 2016-03-11. For some partners this was a significant challenge as they only completed their hardware build the week prior to travelling. All the testing took place in building 07Q at Airbus – this building houses several large test rigs (used for aircraft structure testing) and the rigs were operational for much of the duration of the campaign, generating vibrations and acoustic noise. Building 07Q has industrial-level temperature control and we used this at its normal setting during the first week of operations. This was followed by some days with the system turned off (when the building temperature became quite cold) followed by a morning of re-heating back to normal and then operation at normal temperatures.

Throughout the two weeks, Airbus staff Eszter Szigeti and Matthew Loparco provided logistical support together with relevant health and safety control and Nigel the fitter helped the UCL team assemble their temperature tunnel diagonally up a long side wall of the building.

INRIM started by setting up the two axes of the InPlanT system together with the autocollimator alignment platform. The axes were mounted on the floor, intersecting at the autocollimator table. By moving the platforms further away, larger measurement volumes were simulated.

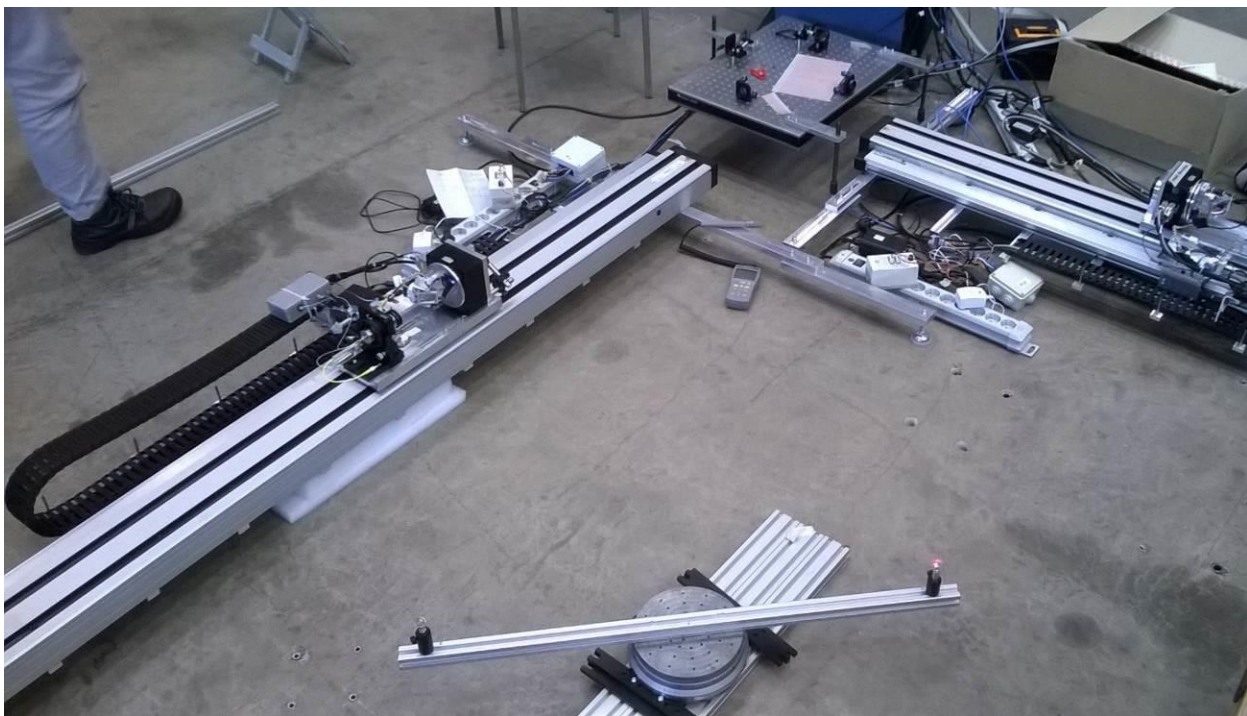


Figure 21 - A 2D version of the INRIM InPlanT system being tested at the Airbus facilities as two measuring axes (sliders, diagonal on left and right). The two axes are angularly linked by an orthogonal pair of autocollimators (rectangular table supporting the op

Due to only having two axes, INRIM had to choose carefully the testing which they could perform. They attached a pre-calibrated ball-bar (of two $n=2$ targets) to a precision rotary indexing table. They rotated the table to 8 different locations and in each location, they used the two InPlanT axes to measure 2D coordinates of the two targets. The resulting data was used for a data fit of the parameters (x_0, y_0) being the centre of the circle, and R_1 and R_2 being the radii of an ellipse (an ellipse was used rather than a circle to allow for non-planarity of the experiment). Initial standard deviation of the fit was $276\text{ }\mu\text{m}$ using only the linear encoders on the axes, and this was improved to $45\text{ }\mu\text{m}$ by including the measured yaws & pitches of the axes' rails and thermal compensation of the rail distances.

UCL had the most physically difficult to assemble experiment whilst at Airbus - a 45 m long 'temperature tunnel'. This consisted of 12 rectangular frames on which four thermocouples were mounted, two each on the



horizontal and vertical members, allowing local horizontal and vertical gradients (and individual temperatures) to be measured. To cope with the cable runs from these sensors, continuous metal channelling had to be fitted to the side of the Airbus building, along a diagonal, from near floor level at one end, to a height of 13.5 m at the opposite end. This required the use of two 'cherry pickers' and assistance from Airbus staff and took all of the first week to complete. At each end of the tunnel, UCL mounted a digital camera with 150 mm long focus lens and a set of coloured LED light sources. Images from the two cameras were captured once every second and a very large (1.5 TB) dataset was generated. Detailed analysis of the data is ongoing but tests using a version of the system installed in a laboratory at UCL has shown the system to be capable of detecting sub arc-second angular change. Photogrammetric errors due to air refraction are just at the limit of sensitivity of the multi-wavelength telephoto camera system. However the identification of long term systematic trends in the data allows an assessment of temperature drift along the sight line over time, due for example to heating and cooling cycles, whilst short term perturbations in the target image position allow an assessment of atmospheric turbulence, due for example to local air movement, to be made. Both measures allow greater confidence in understanding the impact of change in the factory environment on metrology.



Figure 22 - View of diagonal thermal tunnel - 12 thermocouple frames with lower camera/target assembly.



Figure 23 - Upper camera and target assembly (at 13.5 m height).

The University of Bath team based their experimental work around the Airbus wing test jig – a structure some 20 m x 8 m x 30 m in size for which Airbus had sent detailed CAD data to Bath. A laser tracker was mounted on a stable platform within the base of the jig and a network of target nests were fixed to the jig and were occupied by laser tracker targets. A network of Wi-Fi-enabled temperature loggers was placed at pre-designated locations on the jig structure to monitor temperatures. The laser tracker was set to operate an automated measurement sequence and the temperature loggers were remotely interrogated. Data was obtained in normal factory conditions, at cold temperatures during the shutdown of the air conditioning, and during the subsequent re-start and heating period after air conditioning was restored. See figure 17 for details.

The team from Bath also brought along their multi-component assembly rig which was used by NPL and INRIM as part of their network of targets. The data from this experiment is still being processed (due to the detailed nature of the CAD information supplied by Airbus), however previous tests using the multi-component assembly showed significant improvement in the thermal compensation capability available using Bath's hybrid model.

In the first week PTB performed some measurements in absolute distance and fringe counting mode on short paths up to 2 m. The team from CNAM arrived at the start of the second week. In the second week the 3D-Lasermeter and CNAM's Telemeter were placed on the floor at the extension of UCL's temperature sensor tunnel. Both devices targeted the same retroreflector at 44.8 m distance near the ceiling through the sensor tunnel. Similar to the measurement campaign at GUM, PTB concentrated on experiments in the fringe counting mode and evaluated the refractive index changes from the interferometer data. In case of very high



turbulence, unrecoverable beam interruptions occurred. This can be overcome to some extent by a larger beam diameter if this measurement conditions are unavoidable. For moderate turbulence conditions, however, the counting interferometer performed fully within expectations. Lacking a compatible length reference, the refractive index was derived from the optical measurement and compared to the one deduced from the sensor tunnel and Edlén's equation. The results were consistent within some 10^{-7} with the sensor data under stable conditions and deviated up to 5×10^{-7} during the heating of the building with a temperature gradient up to 10 K in the beam path. This deviation can be well explained by the temperature distribution in the building and the lacking of temperature sensors in the lowest 5 m of the path in front of the emergency exit door. The experiment thus perfectly demonstrates the benefit of optically intrinsic refractivity-compensation. The method is more accurate than any other sensor setup as it by design measures the intrinsic temperature along the whole path. Moreover, it is completely flexible and has, other than a free line of sight, little demands on the measurement volume.

NPL arrived part way through the first week and assembled their FSI system comprising the main electronics and computing rack and the four sensor heads. The first task was to align the visible optics of the FSI target location cameras with the infra-red beam steering optics using a pre-made target array and using IR-sensitive card to detect the beam locations. The remainder of the first week then comprised measurement to targets at greater and greater distances (up to the limit of around 10 m imposed by the reference fibre) together with observation of the predicted aliasing of the distance signal at distances greater than 10 m. In the second week, NPL staff set up a target network in cooperation with INRIM such that INRIM's InPlanT system would be able to measure the 2D (planar) coordinates of the targets viewed by the FSI system. A laser tracker was used to fully measure all targets in the network. The network of targets was measured by INRIM up until the point when they had to pack up ready for departure. Unfortunately in the rush to complete measurements, two targets were knocked between the time at which INRIM measured them and before NPL could measure them, so a direct comparison between the two techniques was not possible.

The NPL FSI measurements of the targets were compared with measurements from the laser tracker. Over the $5 \text{ m} \times 5 \text{ m} \times 3 \text{ m}$ measurement volume (size constrained to match InPlanT axes and available lengths of camera cables) uncertainties (calculated by the multilateration software) were around $100 \text{ }\mu\text{m}$ and the length of the pre-calibrated 2.3 m long artefact was measured within $90 \text{ }\mu\text{m}$ of the correct value.

Throughout the second week, NPL also provided environmental data to the other teams: four Raspberry Pi-based loggers were used (one per FSI head) to monitor local conditions (temperature, pressure, humidity). Another similar logger was used with a strip of 20 temperature sensors to monitor the thermal gradient of the air surrounding the wing bending jig and a laser tracker was used to monitor a target attached to the highest point in the UCL temperature tunnel experiment. This laser tracker data clearly showed the movement of the top of the building during windy conditions experienced on the day the heating was turned back on.

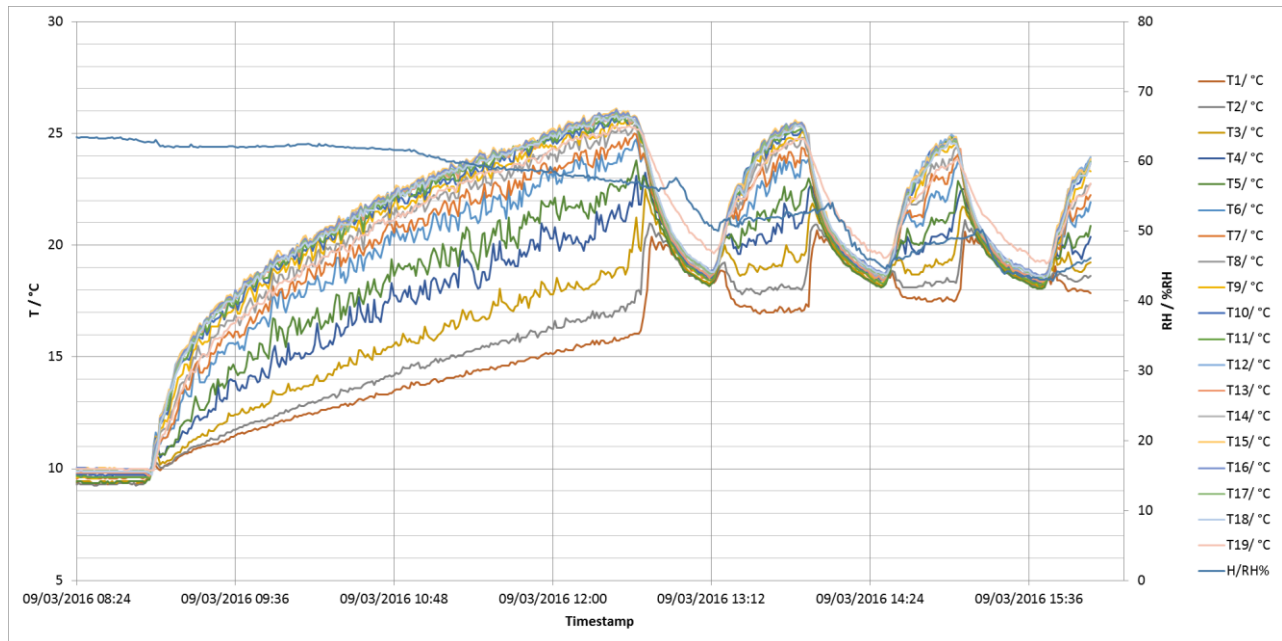


Figure 24 - Data from the logger monitoring humidity and vertical temperature gradients on the large test jig. The facility air conditioning was turned on at 09:00 on 09/03/2016 after several days of inactivity. The pulse nature of the control system is clearly visible as are the 10 °C temperature gradients across the structure.

All partners had departed by lunchtime on the last day of the two week period to analyse data. The two week period saw some equipment (value approximately €0.8M) transported to/from six laboratories in four different countries together with eighteen staff. We were extremely grateful to the staff at Airbus for their cooperation and hosting of the two week visit.

3.6 Additional scientific research

To develop and validate a method for the determination of a reliable spatiotemporal uncertainty of measured trajectories in real-time.

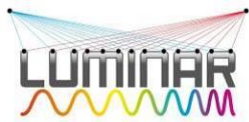
ACHIEVED

A project researcher from the Karlsruhe Institute of Technology was able to tackle an additional objective by significantly advancing knowledge in the field of dynamic measurements in LVM.

Future production processes will focus on shorter production times as well as on more reliable processes. This means that Large Volume Metrology (LVM) has to deliver reliable results, even for kinematic applications, so that e.g. the alignment process of large modules could be quicker than it is currently possible. Cooperative and self-guided robots will replace conventional production methods and demanding in-process proof of quality for spatiotemporal information. This requires the real-time determination of reliable spatiotemporal uncertainties of the arbitrarily moving objects, namely position and orientation, both with respect to time.

Recent research shows, that straight-forward calculations of spatiotemporal uncertainties for LVM using current standards specifications is currently not acceptable, as on the one hand, the behaviour of the measuring instrument observing moving objects is not satisfactorily known, and on the other, analysis methods based on Bayesian theory deliver more precise results as they use additional process information.

In order to achieve a spatiotemporal uncertainty calculation in real time a Bayes filtering technique is applied. The performance and the reliability mainly depend on the description of the kinematic process within the system model and the stochastic model as well as the description of the measurement process. A measurement model for the two types of laser trackers was considered this is the beam steering mirror model and the gimbal mounted beam source model. The required information about the system model can be either estimated via a hybrid system filter approach, or the robot control system can be integrated into the analysis



method. The integrated method uses the information from the robot control system directly, without any additional noise leading to a more reliable state and uncertainty estimate.

The kinematic uncertainty of a laser tracker measurement is also dependent on the meteorology within the measurement volume and the reflector used. During kinematic experiments with a glass reflector like a cat's-eye reflector the centre beam of a laser is not always perpendicular to the outer surface of the reflector. This results in an increased divergence angle leading to an additional deviation of the centroid of the back reflected beam. A crucial part of a meteorology model within a laser tracker analysis method is the refractive index. Unfortunately the common meteorology models only deal with the distance measurements of a laser tracker, the angle measurements are not considered. However, the behaviour of the fluctuating part of the refractive index field is described by the turbulence theory and so a more realistic variance for the angle and distance measurement can be deduced.

To verify the analysis method for kinematic laser tracker measurements a multilateration system consisting of four laser tracers was used to generate a ground truth. Throughout these experiments an industrial robot carried a reflector along certain trajectories at different velocities, while a laser tracker and the multilateration system were measuring it simultaneously. The results of these experiments reveal that the proposed analysis method can be used in real time for process monitoring like assessing robot path deviations. Furthermore, with real time uncertainty information about the trajectory, now external observations like kinematic laser tracker measurements can be suitable used for online corrections of an industrial robot while the actual process keeps running.

3.7 New measurement capabilities:

GUM bench

The 50 m tape bench facility at GUM after the upgrade allows one to perform real-time measurements of refractive index of air *e.g.* along the beam of laser interferometer. The new measuring system with sets of sensors is flexible enough to give the capability of measurements in various scenarios. Multipoint monitoring provides the detailed information about environmental conditions and enables testing and calibrations in simulated industrial conditions. The ongoing research focuses on the development of an optical method for refractive index compensation with use of optical frequency comb.

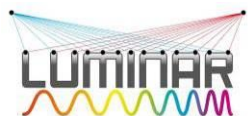
PTB facility

At PTB a new excellence centre for wind energy is set up aiming at the measurements of large gears of up to four metres in diameter and other wind turbine components. To achieve small measurement uncertainties it is planned to set up a multilateration system of four 3D-lasermeters as a metrology frame to the large coordinate measuring machine. This will allow precision measurements and calibrations of large parts by eliminating perturbations of the refractive index of air. The ADM modus of the 3D-lasermeter will significantly facilitate the measurement process.

3.8 Summary

Overall, the project has delivered against all of the technical and scientific objectives and has exceeded the planned number of communication outputs such as submitted papers, conference presentations, training courses and committee work (see below). Additionally, our research has generated five patent submissions, of which, two are already granted. Only one technical development was not completed in the project duration (due to failure of commercial equipment) and one planned demonstration could not be fitted into the timetable and will take place outside the project at a later date.

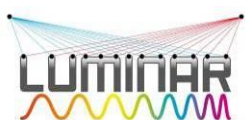
Through our research and development we have delivered 10 totally new measuring instruments or techniques. Their properties are highlighted in the following table.



Technique/instrument/capability	Novelty	Intended use				
		NMI service	NMI R & D	Commercial development	Collaborative R & D	Commercial services
Multi target divergent beam frequency scanning interferometer system	Uses FSI as a distance measuring technique using $n=2$ targets. Divergence from a fibre to obtain moderately wide angle at short range. Gas cell reference for traceability to the metre.					
Multi target long large multi-beam frequency scanning interferometer system	Uses Spatial Light Modulators to achieve high angle divergence of multiple beams from a single measuring head to multiple $n=2$ retro-reflecting targets. Gas cell reference provides traceability to the SI metre.					
Dual camera self-illuminated videogrammetry system	This system was the 1 st to uses through the lens laser illumination & $n=2$ retro-reflecting targets					
Two-axis intersecting planes system (<i>InPlanT</i>)	Separates the sensitive metrology system away from a hazardous environment. In two of the three planes the system is insensitive to the refraction errors which occur due to vertical pressure and temperature gradients.					
Refractive index compensating absolute distance 3D laser meter	System takes the laser tracer concept and adds refractive index compensation along the beam as well as absolute distance capability. In-built traceability via iodine cell.					
Long range refractive index compensating absolute distance telemeter	Uses cheap, off the shelf components to build a highly portable long range absolute distance measuring system with simple traceability via a frequency measurement.					
50 m testing bench with simulated industrial environment with sensors	Most NMIs that have tape benches operate them at 20 °C – the updated bench at GUM can operate over a wide range of temperatures which can be varied spatially and temporally.					
Hybrid modelling system for thermal compensation	Fuses a finite element model with real word data from a limited range of temperature sensors and dimensional monitoring to produce an iterated update to the FEA model that can predict (and this compensate) for thermal distortions away from the sensor locations.					
Refraction analysis and enhanced bundle adjustment software	First photogrammetry bundle adjustment software to incorporate multi-spectral refraction data, allowing detection of beam bending effects due to refraction.					
Digital Centrax camera	World's first pseudo-axicon digital camera, for high finesse photogrammetry target imaging.					

Report Status: PU Public





4 Actual and potential impact

As stated in the project plan, a key route to achieving impact is the stimulation of innovation in LVM and it is through this mechanism that the project is delivering the initial impact by: triggering new research and new collaborations with end users; re-directing existing research; providing training and best practice to the LVM community; influencing specification standards; operating new measurement services; and generating interest from instrumentation companies. In this respect, we have delivered the following routes to initial impact:

- Five patents have been submitted based on the work of the project and two have already been granted: DE 10 2010 032 407 B3 and DE 10 2015 203 697. These five patents have been the basis of two project partners entering into partnership discussions with two commercial organisations, to exploit the developed technology; a partnership agreement is close to signature for one of the partners.
- An existing €0.5M collaboration with the University of South Wales changed direction as a result of the project (*i.e.* the project outputs showed a better route for the research direction).
- The variable temperature environment tape bench with improved sensor systems is already operational at GUM and has been used by two project partners.
- The UK national project *The Light Controlled Factory* (€6.93M funding value) is taking several outputs from the LUMINAR project (the work of University College London and of the University of Bath) and developing them further into a full technology demonstrator in combination with state of the art robotic manufacture and inspection.
- Demonstration of the FSI system to CERN has resulted in a request from them to collaborate to develop the FSI system for their use in various metrology tasks associated with the Large Hadron Collider and in future alignment of its successor; CERN have already purchased target spheres for the FSI system for use in alignment tasks and invited NPL staff to CERN-sponsored workshops on accelerator alignment (the *PACMAN* project).
- The *InPLanT* system has been demonstrated to a machine tool company and this has led to a request to explore further development of the technology.
- There has been a direct request from a commercial organisation to enter into collaboration to develop and exploit the FSI system.
- There has been an early discussion with a commercial organisation to exploit the tracking interferometer.
- We have delivered 8 training courses or workshops on our work, presented at over 30 conferences, submitted 10 articles to peer-reviewed journals, and made representation on four standards committees (International Standard EN ISO 10360-10 2016 contains reference to the work of one of the project partners).
- The Capabilities and Potential report (IP Exploitation Plan) for the project outputs lists 23 items for potential commercialisation or exploitation ranging from cheap environmental loggers based on the Raspberry Pi computer (used inside the FSI measuring heads and standalone devices used on site at Airbus), to exploitation of a developed laser tracker uncertainty mode for dynamic measurements which can be used to improve the accuracy of hand-carried laser tracker targets.
- A new collaboration between University College London and Airbus to develop capability at the new €44.8 million joint investment in the wing integration centre at Filton near Bristol will be using work from the project.
- The National Physical Laboratory has received a request from a national (UK) funding body to submit a proposal for further development of the FSI system into a facility for use by aerospace companies.

Report Status: PU Public





- A plan to set up a calibration service for large coordinate measuring machines using the tracking interferometer is already underway at PTB and NPL is already continuing to improve the FSI prototype system using national funding.

Longer term, impact will come from the medium term further development and exploitation of the project outputs either *via* collaborative R&D or the use of commercial instruments based on the prototypes demonstrated in the project. Once the medium term exploitation is successfully concluded (*i.e.* new LVM services at GUM, PTB, NPL are used by customers; development of INRIM, PTB, NPL outputs are taken up by commercial companies; CERN takes delivery of an FSI system; UCL & UBATH outputs developed further in the Light Controlled Factory demonstrator produce eventual update), the project will have several direct impacts on many sectors:

- Instrumentation: a range of instruments will become available, giving accuracy approaching that of laser trackers but with SI traceability and ability to measure more targets simultaneously and compensate for refractive index effects. At around €100k minimum each unit, commercial instrument sales could lead to significant new EU turnover at the commercial technology partners.
- Science: the Large Hadron Collider's successor will be aligned using technology based on the project research – without accurate alignment, the largest machine ever built will not work - \$7.8 billion direct costs plus 13,000 person years of contributed effort would be wasted.
- Transport: aerospace manufacturing will be using measuring systems coming from project outputs to perform in situ testing of new wings without the need to pause tests to wait for measurements to be made statically; live monitoring of wing assembly jigs will lead to the accuracy improvement (400 μ m down to 100 μ m) required for next generation aero-structures, saving at least 100 kg in weight on each aircraft built and 122 tonnes of fuel/aircraft *p.a.*, leading to a reduction of 38.5 tonnes of CO₂/aircraft *p.a.* and reduced overall operating costs of around €5.5k per aircraft *p.a.*
- Advanced manufacturing / Industry 4.0: factory-wide metrology system will be based at least partly on combinations of technologies from the project, enabling automated robotic assembly and manufacture at necessary accuracy level. A recent [report](#) concluded that an industrial-scale version of the Internet of Things, *i.e.* Industry 4.0, could add \$14.2 trillion to the world economy over the next 15 years. Advanced large scale manufacturing will require the advanced metrology from this project.

We foresee several stages and routes to impact from the project. Some of these are already achieved.

4.1 **Impact route 1 – Dissemination activities**

By the end of the project, we had delivered the following activities:

- **11 publications** submitted to peer-reviewed journals (seven already published – see section 6): these international journals confirm the leading edge nature of the science outputs of the project and contain a selection of metrology, optics, photonics and surveying journals.
- **12 inputs** to standardisation and metrology committees (EURAMET, ISO, VDI/VDE, UNI): we have used our knowledge generated from the research to provide inputs to standardisation and metrology committees which will affect the LVM community – by improving the technical basis for specification standards such as those from ISO we have increased the value for money for users of these standards. In particular we have achieved the following:
- **1 new international standard** (ISO 10360-10) already citing work from the consortium partners: we submitted details of a fast technique for laser tracker performance verification (faster than performing a full test as specified in the draft standard) which is based on the multilateration approach used in the FSI technique – this is now directly referenced in the published standard as an alternative approach.
- **34 conference** presentations and posters: our dissemination work through international and national conferences has exceeded that planned – this is because the importance of LVM has been receiving increased emphasis and we have chosen to target as many end users as possible through both general and invited presentations and posters. Our high quality has been recognised by two best poster awards at the annual LVMC conference and its successor EPMC. We have twice participated in the invitation-only CERN PACMAN workshops on accelerator alignment at the nanometre scale.



- **8 training sessions** (six of which were for external audiences of end users);
we have been recognised as being knowledge leaders in LVM, having been repeatedly invited to deliver training sessions at LVMC/EPMC and participate in the CMSC Measurement Zone multiple times throughout the project duration.
- **3 trade journal articles** have been used to publicise the work in industry;
we have published articles in: the Journal of the Coordinate Measurement Society (ISSN 2328-6067) which is read by several hundred end users of LVM; Quality Manufacturing Today Magazine (<http://www.qmtmag.com/>) which is distributed at many LVM trade shows and to large numbers of end users by post; and in the online magazine Quality Digest (<http://www.qualitydigest.com/inside/cmssc-article/021816-novel-coordinate-measurement-system-based-frequency-scanning>).
- **2 weeks of successful onsite measurement and demonstration campaign at Airbus**;
a major test and demonstration activity was the two-week long measurement campaign which involved most of the project partners taking their prototype instruments and software to Airbus, Filton, where we operated the systems inside a live aerospace factory environment. During the two weeks the instruments were demonstrated to two management teams from Airbus.
- **2 additional inter-partner measurement campaigns** (one at GUM, Poland, one at PTB, Germany);
since LVM tools are usually portable, we ensured that this was the case by arranging another off-site (i.e. away from home location) test of two systems (from CNAM and PTB) in the GUM 50 m facility where the systems were able to be tested to higher accuracy levels in controlled environments and another test of the NPL system at PTB's reference wall.
- **50+ attendees at the end of project workshop** including guest speakers from end users;
our end of project workshop was very successful in attracting a range of speakers and participants from the aerospace, particle physics, astronomy, and large machine tool manufacturing communities. The two day event attracted over 50 attendees and culminated in a discussion session where the outputs of the project were validated as addressing the objectives of the research, as well as identifying new areas where the end user community agreed that further research is now needed.
- **5 patents submitted (2 granted already)**;
the entire €400M European Metrology Research Programme, the total research has generated 20 to 30 patents – in this single project (LUMINAR) we have submitted 5 patents in total and 2 have already been approved – the LUMINAR research thus represents around 20 % of the total patent portfolio of the EMRP, which is extraordinary value for money given that the project received less than 1 % of the available funding. The patents have already triggered commercial interest in exploiting the project outputs (see below). For information the patents are:
 - PCT/GB2013/050838 Coordinate measurement system and method;
 - GB1411206.4 Dual Laser Frequency Sweep Interferometry System and Method;
 - PCT/GB2013/050837 Measurement device, system and method;
 - DE 10 2010 032 407 B3 Laser-Längenmesssystem (laser length measuring system) – GRANTED;
 - DE 10 2015 203 697 Laser-Längenmesssystem (laser length measuring system) – GRANTED.
- **4 follow-on collaborations** between different groups of the project partners;
The project has led to further collaborations between different mixtures of project partners:
 - NPL & University of South Wales (1 collaboration changed direction, 1 collaboration on shared IP);
 - UK nationally funded project The Light Controlled Factory will take outputs from LUMINAR participants University College London, NPL and the University of Bath and develop them further;
 - A new collaboration between University College London and Airbus in structures testing has been set up to ensure that the €44.8M Airbus / UK Government investment in the wing integration centre will have the large volume metrology capability necessary to develop the next generations of civil aircraft wings.
- **6 requests for end-user uptake of the project outputs**;
the project partners have already received six requests from end users for access to (or collaboration on), the project outputs and knowledge:
 - 3 requests from CERN for supply of FSI hardware and knowledge transfer/collaboration;



- An invitation from the Aerospace Technology Institute to bid for funding to further develop the FSI system into a commercial application
- 2 discussions with metrology companies concerning commercial uptake/licensing/collaboration of project outputs.

4.2 Impact route 2 – NMI exploitation – Impact on NMI Metrology

The impact from the JRP is initially provided by the direct use of the outputs by the JRP-Partners: GUM will operate new services using the improved tape bench; PTB will use their device to calibrate large scale objects, perform measurements in tooling machines and further development of their M3D3 software/hardware and other techniques, thus establishing new traceability routes for LVM; NPL will use the FSI system as a reference metrology tool for verifying other techniques and the technique will be developed further; CNAM will have a new device for medium range length metrology; INRIM will develop the InPlanT system from a 2D demonstrator into a 3D working system from which they can assess the potential market in addition to seeking exploitation of the underlying concept. Thus the NMI community will immediately have new facilities to offer to internal and external customers as well as new bases for further research.

4.3 Impact route 3 – commercial products – Impact on Industry

Second stage impact will be *via* metrology companies using JRP IP in new products: here the NPL FSI system and the PTB absolute compensated tracer are actively being discussed with metrology companies already and there are similar possibilities for other JRP outputs. We make the assumption here that in the 5 years after the JRP ends, the IP collaboration/licensing with the metrology companies is successfully concluded and that new products from these companies are starting to be developed or sold. This is a realistic timescale for this activity as the marketplace for the new products already exists and time to market will be important for commercial opportunities. The inclusion of SIOS in the design and build of the PTB device means it is already in a commercially-ready format. The technique developed by UCL can be implemented in existing photogrammetry systems. The NPL FSI system is based on components from the telecommunications industry that are readily available. Direct impact for the NMIs concerned and the commercial organisations will be income from sales, but also new spin off ideas.

4.4 Impact route 4 – end users using new tools & techniques: economy & society impact

From the very start, a key goal of the project has been to deliver new devices and techniques which are not just for NMI use, but can be commercialised to reach a wider user-base. Within 5 years, the refractive index compensation from UCL will be in use when they are making measurements in non-ideal environments, allowing them to work in locales they would previously have discounted. Variants on the technique will be in use by other photogrammetry users (subject to IP) and existing photogrammetry setups will be adapted to perform this compensation, when required. This will include automotive, aerospace users setting up new, large equipment as well as organisations like CERN, who will be starting to survey the tunnel and prepare for alignment of sub-assemblies of the LHC successor, or at least be planning them. In long tunnels, the refraction effect can be very large (it scales as the range squared) – it can be several millimetres over a 100 m range. The UCL refraction and CNAM refractive index compensation will reduce such effects in these environments. Other large science experiments (ESRF, ITER) which have dedicated survey teams will benefit likewise (we are already in contact with survey scientists at ESRF).

In industry, especially aerospace and large engineering (e.g. new nuclear build, energy infrastructure, marine) we foresee the commercialised FSI system used to align and monitor large jigs (e.g. for aircraft wings and fuselages), to track probing systems used for on-machine metrology, to monitor positions of robots and their end effectors, to track manipulators and components in 6DoF as they move into position in large machining centers. Thermal compensation will be achieved using temperature sensors and simple dimensional sensors, feeding information into a hybrid model based on the technique developed by UBATH, which uses Kriging-like methods to modify FEA models based on all available data, updated in near real-time. Likewise, the large machine tools which will be cutting valuable components from specialist materials for civil nuclear reactor components will be error mapped using devices such as the PTB compensated tracer. Such machine tools will be operating in non-ideal environments where classical laser tracers and trackers will not be able to compensate for refractivity effects. The use of PTB's compensated tracer thus will significantly reduce the achievable measurement uncertainties leading to leaner production processes and reducing production tolerances.



The key market for technology developed by and as a result of the JRP will include the advanced high value manufacturing sector (including aerospace, new energy build) where the impacts will be associated with economic growth as well as the environment. Furthermore, science and construction sectors with large civil engineering projects (e.g. LHC successor) will be an additional impact route in terms of being able to deliver the required accuracy to achieve their goals, leading to societal advances coming from leading edge science. Finally, we anticipate a somewhat smaller impact in the public health sector where improved alignment of beam line systems for cancer treatment will increase the efficacy and throughput of treatment rooms connected to small synchrotrons.

Within 5 years of the end of the project, we anticipate that several JRP Outputs or systems relating to them will be in use by aerospace users, for example using FSI systems for aerospace jig monitoring; using laser tracer devices for machine error mapping; refractive index and thermal compensation (UCL and UBATH). The users of these devices will be manufacturing large aircraft components to better accuracy in fulfilment of their goals in the Clear Skies initiative (the requirement is to achieve 100 μm over the wing and current SOA is 400 μm). This has a double fuel saving routes: weight saving and transition to natural laminar flow designs. A moderate saving of just 100 kg in a single aircraft (which we believe is moderately achievable) will save: 122 tonnes of fuel/aircraft *p.a.*, leading to a reduction of 38.5 tonnes of CO₂ /aircraft *p.a.* and reduced overall operating costs of around €5.5k per aircraft *p.a.* The worldwide airliner fleet is set to grow by another 40,000 aircraft in the next 20 years, with a 100 kg weight reduction through metrology this represents an annual cost saving of €220M. There would be additional fuel savings due to aerodynamic drag reduction on a laminar flow wings – NASA estimates 10 % to 25 % reduction in fuel burn.

Economic growth will come from the high value of aircraft being manufactured – the current European aerospace turnover is €94.5 bn and 29,000 new aircraft are planned for manufacture by 2030, with a total value of €2.3 trillion value – any small improvement to the efficiency of the manufacturing process (e.g. reduced downtime from jig inspection) will have high absolute savings. Secondary financial impacts will come from savings passed on to those who use air transportation – European aviation's economic impact is estimated as €270 bn *p.a.* [Air Transport Action Group report (2008)].

We envisage that the UCL and CNAM devices will find uses in large civil engineering projects such as the construction and alignment of the LHC successor (CLIC/ILC) where, according to current design plans, the 25 km long tunnel will require sub-assembly alignments to 10 μm uncertainty every 200 m. Key issues here are the difficult linear nature of the construction (lateral accuracy is difficult to achieve with conventional instruments due to lack of stand-off and refraction effects). CERN are actively looking for new technologies to advance the current SOA (100 μm to 300 μm) to be able to achieve their goal (for information, the 25 km long beams in CLIC/ILC are 4 nm wide).

With the global energy crisis, several economies are turning (or returning) to civil nuclear build. New reactor construction uses specialist high value materials on long lead times; machining of these large structures needs in situ metrology to avoid costly errors and long delays. The NPL and PTB outputs are ideally relevant to metrology provision for in situ metrology on large machining systems as they both operate up to 10 m or 20 m range and can monitor/map large machine tools.

In addition to the impact to be generated by the main project outputs stated above, our *Capabilities and Exploitation Report* lists 23 items of foreground IP generated by the project (in addition to the 5 patents) which we intend to exploit further (full details are available from the project website – see later). A shortened description of these items follows.

- Calibration services for large volume coordinate measurement machines (CMMs) using 3D lasermeter.
- Multi-target divergent beam frequency scanning interferometry.
- Multi-target frequency scanning interferometry (long range).
- Targetless frequency scanning interferometry.
- Vibration compensation in frequency scanning interferometry based on reverse scan generations using four wave mixing.
- Flexible cheap environmental loggers based on open source software tools and cheap Raspberry Pi computers. Ideally suited for *Internet of Things* applications.
- Hybrid Metrology system utilising mixture of physical and computational measurements.
- Temperature measurement planning method which is an improvement on existing linear scaling methods
- Design of high resolution distance measuring system using cheap off the shelf opto-electronics.



- Second fibre-optic telemeter unit operating at 785 nm wavelength.
- Updated tape bench system.
- Variable environment tape bench system.
- Refractive index compensating interferometer.
- Pointing and tracking system.
- Two-axis metrology system.
- Compensation for common refraction effects.
- Uncertainty evaluation for dynamic measurements in real time.
- Laser tracker uncertainty model for dynamic measurements.
- Multilateration network solution quality evaluation technique. Detects poor user-design of metrology network solution modelling.
- Robotic dynamic path deviation detection in real-time.
- Refraction analysis.
- Enhanced bundle adjustment incorporating refraction.
- Digital Centrax camera.

We anticipate that many of these items will be used in future projects, research, services and products, generating additional impact. For example, UCL is developing the Digital Centrax camera using further funding from a UK nationally-funded project and the Raspberry Pi loggers designed by NPL have already been supplied to several other parts of NPL, to one accredited laboratory in the north of England, and have been requested by another accredited laboratory, and several 3rd parties have already downloaded the open-source instructions on making these devices and have started to implement them. In a new development, we have demonstrated to CERN the ability of the FSI system to accurately detect the position (and diameter!) of the 100 μm alignment wire used to align the LHC, showing that this system is ideally placed for use in accelerator alignment.

Aside from the scientific and business impact of the project, in regulatory terms, the outputs of the JRP (new knowledge, improved measurement methods and systems) will impact on several Directives by enabling the Directive to be effectively applied through appropriate measurements. For example, reduction of drag and airframe noise by enabling laminar flow concepts would reduce noise from aircraft on approach to land at airports. Measurement of storage locations by LVM tools with better accuracy would enable faster assessment of stability of locations for storing energy sources and waste products, e.g. gas, carbon dioxide and nuclear waste. Directives thus impacted include:

- Directive 2004/22/EC (measuring instruments) in which Annex MI-009 directly governs Dimensional Measuring Instruments;
- Directives relating to aviation efficiency and aircraft noise at airports, *i.e.* Directive 2008/101/EC (the 'Aviation Directive'); Directive 2002/30/EC (noise at airports);

Large facilities, such as power stations, infrastructure projects, etc. are subject to the provisions set out in various Directives. The assessment of impact on the environment for such large constructions often requires monitoring of local subsidence or earth movement (e.g. excavations near to existing underground facilities). These may fall within the range of extended range LVM equipment and thus the project will support:

- Directive 2009/31/EC (geological storage of carbon dioxide);
- Directive 2011/70/EURATOM (framework for nuclear waste and spent fuel storage).



4.5 Summary of outputs and impact

This project has produced a range of new techniques, instruments and knowledge that will enable LVM users to deliver their own advanced products, facilities, and measurement services which will all make contributions to society either by being more efficient, or generating higher impact/ new science, using fewer manufacturing resources & creating less scrap/waste, etc.

In summary:

1. We produced all the outputs specified in the project plan.
2. We successfully achieved all the project scientific objectives.
3. Project outputs have been demonstrated to end user communities.
4. Project outputs have been validated by the stakeholders as satisfying the objectives of the research.
5. We have listed several examples of early stage impact already generated by the project.
6. Several project outputs are already in use at project partners.
7. Project outputs are being developed further under new research collaborations.
8. New research collaborations have been triggered by the project and this interest continues to be expressed by those who see the new technologies we have developed.
9. Some project outputs are very close to being developed into commercial products by metrology companies and we are actively pursuing this venture.

“We Shape Our Tools, and Thereafter Our Tools Shape Us”

5 Website address and contact details

The project maintains two websites, an internal SharePoint for project partners (private) and a public website:

www.emrp-luminar.eu

The contact for the website is the project coordinator Andrew Lewis (andrew.lewis@npl.co.uk), +44 20 8943 6074.



6 List of publications

6.1 Journal papers

- Warden M S, [Precision of frequency scanning interferometry distance measurements in the presence of noise](#), *Applied Optics*, **53** 580-558 (2014)
- Ulrich T, [Uncertainty modelling of real-time observation of a moving object: photogrammetric measurements](#), *Metrologia*, **52** (2) 201-213 (2015)
- Martinez J J, Campbell M, Warden M S, Hughes E B, Copner N, Lewis A, [Dual-sweep frequency scanning interferometry using four wave mixing](#), *IEEE Photonics Technology Letters*, **27** (7) 733-736 (2015)
- Ulrich T, [Uncertainty Estimation for Kinematic Laser Tracker Measurements](#), *IEEE Explore*
- Lewis A, Campbell M, Stavroulakis P, [Performance evaluation of a cheap, open source, digital environmental monitor based on the Raspberry Pi](#), *Measurement*, **87** 228-235 (2016)
- Robson S, MacDonald L, Kyle S, Shortis M R, [Close range calibration of long focal length lenses in a changing environment](#), *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLI-B5** 115-122 (2016)
- Ross-Pinnock D, Yang B, Muelaner J, Mullineux G, Temperature interpolation in a hybrid approach to dimensional metrology, submitted to *Measurement*
- Meiners-Hagen K, Meyer T, Prellinger G, Pöschle W, Dontsov D, Pollinger F, [Overcoming the refractivity limit in manufacturing environment](#), *Optics Express*, **24** (21) 24092-24101 (2016)
- Ulrich T, Analysing Multilateration Measurements to Generate a Ground Truth for Kinematic Laser Tracker Measurements (submitted to *Journal of Geomathematics*)
- Yang B, Ross-Pinnock D, Muelaner J, Mullineux G, Thermal compensation for large volume metrology and structures (submitted to *International Journal of Metrology and Quality Engineering*)
- Robson, MacDonald, Kyle, Boehm, Shortis 2016. [Optimized multi-camera systems for dimensional control in factory environments](#). *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (2016): 0954405416654936

6.2 Trade journal articles

- Campbell M, Hughes E B, Veal D, [A Novel Coordinate Measurement System Based on Frequency Scanning Interferometry](#), *Quality Digest Magazine*, Feb 2016
- Hughes E B, Warden M S, [A novel co-ordinate measurement system based on frequency scanning interferometry](#), *Journal of the CMSC*, ISSN 2328-6067 (2013)
- Shining a light on challenges in Large Volume Metrology, *QMT Magazine*, (submitted for October 2016 issue).

6.3 Good practice guide

- [Coping with Thermal Expansion in Large Volume Metrology](#)

6.4 Conference proceedings

- Campbell M, Hughes B, Lewis, A, [A high-accuracy, self-calibrating and traceable coordinate measurement system](#), CMSC 2016, Jul 2016, Nashville, USA
- Robson S, MacDonald L, Kyle S, Shortis M, [Close range calibration of long focal length lenses in a changing environment](#), ISPRS 2016, Jul 2016, Prague, Czech Republic
- Campbell M, Hughes B, Lewis A, [Recent developments in the field of frequency scanning interferometry](#), Invited presentation at CERN PACMAN workshop, Jun 2016, Debrecen, Hungary
- Lewis A, [The LUMINAR project](#), Invited presentation at CERN PACMAN workshop, Jun 2016, Debrecen, Hungary
- Wallerand J-P, Guillory J, [Télémétrie optique à deux longueurs d'onde](#), Journée du Club Optique et Micro-Ondes, Jun 2016, Nice, France



- Campbell M, Hughes B, [A high-accuracy, self-calibrating and traceable coordinate measurement system](#), euspen 2016, May 2016, Nottingham, UK
- Balsamo A, Egidi A, Francese C, Pisani M, [1D measurement of coordinates in space: a novel apparatus](#), euspen 2016, May 2016, Nottingham, UK
- Mullineux G, Muelaner J, Ross-Pinnock D, [Thermal compensation of photogrammetric dimensional measurements in non-standard an-isothermal environments](#), DET 2016, Mar 2016, China
- Hughes E, Copner N, Keynote on driving innovation by collaboration, Venturefest Wales 2015, Sep 2015, Cardiff, UK
- Robson S, [Optical metrology with low-cost camera systems for advanced manufacturing](#) (Invited Paper), SPIE Conference 9528: Videomatics, Range Imaging and Applications XIII, Jun 2015, Munich, Germany
- Campbell M, [Developments in Multi-Target, Wide-Angle Frequency Scanning Interferometry](#), EPMC, Nov 2015, Manchester, UK
- MacDonald L, [Reducing the effects of refraction on photogrammetry in LVM](#), EPMC, Nov 2015, Manchester, UK
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- Campbell M, Hughes B, Lewis A, Martinez J, Copner N, [Multilateration with frequency scanning interferometry and four wave mixing](#), LVMC, Nov 2014, Manchester, UK
- Lewis A, [The LUMINAR JRP - Large Volume Metrology in Industry](#), LVMC, Nov 2014, Manchester, UK
- Robson S, Kyle S, MacDonald L, Shortis M, [Towards understanding photogrammetric refraction in large volume metrology](#), LVMC, Nov 2014, Manchester, UK
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7 Research teams and their outputs


The research was performed by a large team of scientists and engineers across five national metrology laboratories, 3 universities and 3 unfunded industrial partners. We acknowledge here their research teams.

7.1 Research teams of the JRP-Partners


	Conservatoire national des arts et métiers 292 Rue Saint-Martin 75141 Paris Cédex 03292 France
Senior researcher Jean-Pierre Wallerand was assisted by Joffray Guillory, Daniel Truong, Christophe Alexandre and Radek Smid.	

	Główny Urząd Miar Elektoralna 2 Warszawa Poland
The research team at Główny Urząd Miar comprised Marius Wisniewsky and colleagues Robert Szumski and Dariusz Czulek.	


	Istituto Nazionale di Ricerca Metrologica Strada delle Cacce, 91 IT-10135 Torino Italy
Lead scientist for INRiM was Alessandro Balsamo, who was able to draw on the expertise of Claudio Francese, Marco Pisani, E. Audrito, D. Corona and Andrea Egidi.	


	National Physical Laboratory Hampton Road Teddington TW11 0LW United Kingdom
The research team, led by Ben Hughes included Matthew Warden, Dan Veal, Andrew Lewis and Michael Campbell. Andrew Lewis was the project coordinator. We acknowledge support from the NPL Engineering Workshop and financial co-support from the National Measurement System Engineering Measurement Programme funded by the Department for Business Innovation and Science.	



	Physikalisch-Technische Bundesanstalt Bundesallee 100 38116 Braunschweig Germany
The large PTB research team spanned two different groups and included senior researchers Karl Meiners-Hagen, Matthias Franke, Florian Pollinger, Klaus Wendt, Kerstin Rost and Günther Prellinger together with Daniel HeißeImann who assisted during the onsite work at PTB of NPL. The senior researchers were assisted by Martin Wedde, Jennifer Bautsch, Kimberley Smith-Rösler, Patrik Knigge and Tobias Meyer.	

7.2 Integral REG research teams


	The University of Bath Claverton Down Road Bath BA2 7AY United Kingdom
The original researcher on the project was Harry Chu. He was followed by Bingru Yang and then David Ross-Pinnock together with Jody Muelaner. Supervision was initially under Paul Maropoulos and then Glen Mullineux.	

	University College London Gower Street London WC1E 6BT United Kingdom
This research was performed by Lyndsay MacDonald and Stephen Kyle under the guidance of Stuart Robson.	

7.3 Stage 3 REG grant recipient

	The Geodetic Institute Karlsruhe Institute of Technology Englerstraße 7 76131 Karlsruhe Germany
The project benefited from an additional university researcher which received funding under an EMRP Stage 3 researcher grant. This research was performed by Thomas Ulrich under the guidance of Maria Hennes.	

7.4 Unfunded Project Partners teams

	Airbus Operations Limited New Filton House Filton Bristol BS99 7AR United Kingdom
The project team is extremely grateful for the support of Airbus as both a stakeholder and a member of the	



consortium. Airbus kindly donated two weeks of access to building 07Q at their Filton UK site for the JRP team to use as a live industrial test location. As well as providing a challenging environment through the operation of several hydraulic test machines, they kindly allowed us to drop the factory temperature to 10 °C for several days. We gratefully acknowledge the kind assistance of Eszter Szigeti and Matthew Loparco and Nigel the fitter who helped us assemble our 30 m refraction tunnel diagonal up the side of the building.



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NUCLEAR AMRC
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Unfortunately, we ran out of time at the end of the project (due to equipment damage in transit between partners) to make use of the offer of a test location, provided by the University of Sheffield, operating under the two Catapult Centres of the Advanced Manufacturing Research Centre and the Nuclear Advanced Manufacturing Research Centre. Between them, these two organisations offered an array of interesting large volume manufacturing tools which we could use as test beds for the NPL FSI system. Nevertheless, we plan to visit them in the near future to see what can be achieved.

We thus acknowledge the encouragement of Richard James and Carl Hitchens.



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