

# **National Measurement System**

## **Metrology Programme for Time, Frequency & the Metre 2006 - 2009**

**Public Release Version**

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## **Executive Summary**

This document outlines the projects that have been developed for the Department of Trade and Industry's (DTI's) National Measurement System (NMS) 2006-2009 Time, Frequency & the Metre Programme. The projects summarised here represent the scientific programme over the three years from 1st October 2006 to 30th September 2009 to be carried out at the National Physical Laboratory (NPL). They were approved by the programme's Measurement Advisory Committee Working Group in July 2006.

The new programme is an amalgamation of the old NMS Time programme and projects from Theme 1 of the old NMS Length programme. This reflects a change of emphasis in optical frequency metrology from providing traceability for length (which it will continue to do) to the long-term development of an optical redefinition of the SI second. This trend is reflected in the new TFM programme by a shift in effort from research and development into microwave fountains (which realise the current primary frequency standard) to the development of clocks based on a long-lived optical transition in a single trapped ultra-cold ion. In addition, the programme will for the first time start work on the development of a novel optical frequency standard based on a lattice of cold atoms that is predicted to have stabilities well beyond what can presently be achieved. These projects should ensure that the NMS plays a significant role in informing the international discussions regarding the SI second redefinition. A significant part of the programme is directed to support the new development of the European satellite navigation system, Galileo, which will become operational during the course of the new programme. Finally, optical frequency dissemination will be a core activity within the new programme. Frequency metrology has changed dramatically during the last decade since the development of the femtosecond frequency comb that allows for easy comparison and transfer. The new programme aims to fully exploit the properties and applications of femtosecond combs.

Projects were developed using a new project initiation and development process that is being introduced across all NPL science programmes. The programme theme structure allows a coherent grouping of projects and leads to scientific teams with more focus. In addition, we believe that the proposed projects position the programme well for the implementation of the NMS Strategy Review, so that any likely re-allocation of projects can be carried out with minimum disruption to the programme and to scientific work.

### **Rationale**

Time is used directly or indirectly in nearly every aspect of our lives. From the BBC time pips and the speaking clock to the time and frequency signals that are intimately linked with satellite navigation systems such as GPS. At the highest levels of accuracy, time and frequency standards support the exploration of new science from radio-astronomy to atomic physics. The metre and optical wavelength metrology provides traceability to the metre at the top level for all means of realisation of length and dimensional measurements. The measurement of length is of fundamental importance to industry and business and is vital to support trade. It underpins industrial competitiveness, product development, innovation, compliance and improvements in the quality of life, across a diverse range of industries, including construction, manufacturing and processing, aerospace, automotive and defence and communications.

## **Objectives**

The objectives of the programme are:

- To maintain and develop the UK national time standard as part of the international time scales, International Atomic Time (TAI) and Coordinated Universal Time (UTC).
- To realise and maintain the primary metre standard and international consistency.
- To provide the major time and frequency user communities in the UK with access to the national time and frequency standard, either by broadcasting time signals or by validating third party time signals and equipment.
- To disseminate the unit of length to UK industry and other beneficiaries.
- To facilitate the exchange of information and advice on time, frequency and wavelength matters within the time and frequency user communities in the UK.
- To promote UK innovation by removing measurement barriers in the DTI's target impact areas.

## **Appraisal**

The programme has been developed over of a period of consultation from September 2005 to July 2006 involving extensive contacts (meetings, focus groups, one-to-one discussions) with representatives of industry, academics, public bodies, other government departments and other National Measurement System programmes and the public. In addition, an Internet-based consultation process was carried out alongside the face-to-face meetings to ensure that the widest range of opinions was captured. This process was also used to identify potential industrial and academic collaborators for the new programme.

The detailed content of the proposed programme was decided at a meeting of the programme's Measurement Advisory Committee Working Group on 20th July 2006 using the Multi-Criteria Analysis methodology under the guidance of the Strategic Policy Analysis team of the Department of Trade and Industry.

## **Monitoring**

The programme will be monitored through monthly reports to the Department of Trade and Industry's programme officer and through annual meetings of the Measurement Advisory Committee Working Group. In addition, the Executive Committee of the National Physical Laboratory oversees all science programmes carried out at NPL, taking advice on the scientific content and impact of the work from the Royal Society and the Royal Academy of Engineering.

## **Evaluation**

The programme will be subject to continued evaluation using the new "rolling formulation" process proposed by the recent National Measurement System Strategy Review. Projects that appear to be at risk owing to their producing insufficient or reduced impact will be put on notice that they may be terminated and replaced with new projects that are more attuned to the needs of the UK economy.

# Importance of time & frequency measurements to the UK economy

## Time and the second

The global time standard is Co-ordinated Universal Time. UTC is based on measurements of over 200 atomic clocks in some forty national time laboratories around the world, and is computed by the Bureau International des Poids et Mesures (BIPM). UTC is a time scale - i.e. a standard for agreeing the time-of-day - but can also be seen as a measurement system. The seconds of UTC are explicitly related to the SI definition of the second, and hence they provide a mechanism for distributing standards for time interval and frequency measurements around the world.

UTC is a post-processed time scale, and so it is necessary to gain access to one of the national standards to be able to use UTC in real time. The convention is that UTC is the global (post-processed) standard, while  $UTC(k)$  denotes laboratory  $k$ 's representation of UTC. For example,  $UTC(NPL)$  is the time standard at NPL in the UK while  $UTC(USNO)$  is the time standard at the US Naval Observatory in Washington. The BIPM publishes their *Circular T* each calendar month, which lists the differences between UTC and  $UTC(k)$  at five day intervals for each of the forty  $UTC(k)$  laboratories. Hence it is the BIPM Circular T that establishes the degree of equivalence between the various national time standards around the world.

Hence, UTC is maintained predominantly by commercial atomic clocks but the rate of those commercial clocks is calibrated by the few primary frequency standards in the system. The development and operation of primary frequency standards should be seen as one of the main responsibilities of a national time laboratory. Other organisations can and do operate their own time standards using the same technology as the UTC laboratories. Satellite navigation system operators such as GPS are the obvious examples. However, national metrology laboratories are the only organisations whose mission it is to realise the SI units at the highest level of accuracy. It is this mission that is the reason why the NMS supports the UK's contribution to UTC through the NMS Time, Frequency & the Metre Programme.

## Wavelength and the metre

Optical wavelength metrology is central to the NMS in its current and future provision of the realisation of the metre, and its dissemination to UK science, technology and industry. It also ensures consistency of the UK primary metre with international standards developed and maintained at other national standard laboratories, through intercomparison and collaboration. It provides for refinement of high-accuracy working standards, providing traceability for existing scientific, technological and industrial measurements. It also seeks to establish new and innovative primary standards and metrology to service future precision engineering, length and wavelength metrology, spectroscopy and telecommunications developments.

The demand for high-accuracy length, wavelength and optical frequency measurement covers diverse applications across a wide range of magnitudes. In the dimensional area, for example, distance or displacement measurements with precision/accuracies from picometres to millimetres, across ranges from nanometres to kilometres, are all ultimately traceable to the SI metre and its UK realisation. Most of the high-accuracy measurement techniques in this area make use of wavelength or optical frequency sensing techniques. Typical examples of

this include laser interferometer calibration of CNC machine tools and co-ordinate measurement machines: commercial laser-based instrumentation is widely used both nationally and internationally for this purpose. Research and development on optical frequency standards underpins traceability for such activities, both directly through calibration access to primary laser standards, and indirectly through second-level calibration services.

Optical frequency standards, and associated techniques in wavelength metrology, have parallel application in optical telecommunications, where the relentless increase in transmitted data volume and speed place strong demands on the need to significantly expand the existing region of frequency space around the infra-red optical communications bands in order to provide more frequency channels. Techniques for spectral characterisation of wavelength-division multiplexed channels are at the heart of efficient data distribution and recovery, and ready access to frequency standards across this whole region is a strong requirement. High-resolution spectroscopic and astronomical instrumentation also requires a variety of wavelength-specific calibrations, with outputs in chemistry, fundamental science, space exploration and space communications.

Precision length metrology also plays a key role in the realisation of derived units, for example pressure and current. The highest accuracy optical frequency measurements also contribute to the determination of fundamental physical constants, such as the Rydberg and are presently being considered as a possible new primary frequency standard.

### **The national time scale**

The UTC standard can be distributed from the UTC(k) laboratories out to the wider user base by telephone, Internet and radio broadcasts. Often, time signals derived from more than one UTC(k) laboratory can be received at any one location. In the UK, the NMS supports the MSF 60 kHz standard-frequency and time signal. However, GPS time signals (derived from the US Naval Observatory) and DCF77 time signals (derived from the PTB in Germany) can also be received throughout the UK. The diversity of time signals gives UK users greater choice and is welcomed by the NMS. The UK national time standard can be used to validate third party time signals and confirm that they are fit for purpose in the UK. Such monitoring and validation schemes are an extremely cost-effective way of disseminating time and frequency standards at the highest levels of accuracy.

UTC is a measurement standard that permeates all aspects of our lives, both in high precision applications (e.g. geodesy, telecommunications) and for time at relatively low accuracy to co-ordinate our every day activities. Time standards affect everyone in some shape or form and there are just a few institutions around the globe that maintain this facility for all. As a group, it is essential that those institutions are properly resourced, and that any changes in support for individual institutions are managed in a responsible way.

### **Beneficiaries of the Programme**

Having identified the time standard and the dissemination routes, it is worthwhile identifying the beneficiary communities. There are a large number of users who gain access to standard time through third party time signals such as GPS rather than directly from the UK national time standard. Some examples of such user applications are: synchronising telecommunications and broadcast networks; synchronisation and fault-location in electricity grids; time scales used in satellite navigation systems; lightning detection systems; synchronising time servers in computer networks; time-stamping for data loggers;

synchronising clocks and monitoring systems for transport applications - rail, sea, road and air; etc. A number of the above applications will also be served directly by the NMS Time Programme where time signals are actively broadcast (i.e. MSF and telephone time services).

The direct beneficiaries of the Programme are much smaller in number, but they have a broad impact on the UK economy as a whole. First and foremost, the UK national time standard is used to provide traceable time and frequency measurements in the UK. There are over 90 UK laboratories that receive the NMS Time and Frequency Measurement Bulletins to validate their frequency measurements. Those laboratories will provide recalibration services that eventually will encompass all of the UK's accredited and traceable measurement capability. With quartz oscillators being used widely in many electronics products, and in most communications products, the reach of the Programme is very wide. The other direct beneficiaries are the manufacturers and suppliers of precision time and frequency equipment. The interaction between those companies (who are in regular contact with potential customers for time and frequency measurements) and the NMS Time Programme has been most valuable in keeping the Programme in touch with user needs.

In addition to maintaining the national time scale, and the MSF broadcasts, the NMS supports a number of frequency metrology activities in other programmes. The RF & Microwave standards in the Electrical Programme are a good example of where it makes more sense to include particular frequency metrology activities in a sector focused programme rather than in a foundation activity, such as the time scale. However, the boundaries between metrology for particular market sectors and metrology for the base unit are not always clear-cut.

## **Objectives**

To summarise the top-level objectives of the Programme are:

- To maintain and develop the UK national time standard as part of the international time scales, International Atomic Time (TAI) and Coordinated Universal Time (UTC).
- To realise and maintain the primary metre standard and international consistency.
- To disseminate the unit of length and related derived standards to UK industry and other beneficiaries.
- To provide the major time and frequency user communities in the UK with access to the national time and frequency standard, either by broadcasting time signals or by validating third part time signals and equipment.
- To facilitate the exchange of information and advice on time and frequency matters within the time and frequency user communities in the UK.
- To conduct research and development that enables technical and scientific leadership and has potential to deliver ultimate benefits to the economy, and/or society at large.

## The structure of the programme

The programme has been designed around three scientific themes plus projects covering knowledge transfer and management. The rationale for the proposed new theme structure is to present the work in such a way that industry can more clearly identify what it is that the programme offers and can relate it to their own applications and requirements, that is, the themes are defined to be more outward-facing than the current programme themes and less a list of metrology disciplines. In addition the themes reflect the anticipated structure of the NMS programme review in order to facilitate an easy migration into that new structure. The proposed scientific themes are:

- Theme 1: Atomic Frequency Standards, this theme is concerned with the long-term provision of the SI unit of time and the metre and as such underpins the whole of the programme.
- Theme 2: Time scale realisation and dissemination, this theme is concerned with the provision of the national timescale. The outward focus is on the growing impact of GNSS time and location applications.
- Theme 3: Optical frequency dissemination, this theme is concerned with the provision of traceability to the dimensional metrology community and optical telecommunications industry, as well as underpinning the research and development of optical frequency standards under theme 1.

Projects were developed using a new project initiation and development process that is being introduced across all NPL science programmes. The new theme structure allows a more coherent grouping of projects and leads to scientific teams with more focus. In addition, we believe that the proposed projects position the programme well for the implementation of the NMS Strategy Review, so that any likely re-allocation of projects can be carried out with minimum disruption to the programme and to scientific work.

### **Theme 1: Atomic frequency standards**

This theme, through the provision of atomic frequency standards in both the microwave and optical regions of the spectrum, is central to the current and future provision of the SI unit of time. It also provides the top-level traceability with which to realise the SI unit of length by means of the fixed value for the speed of light. The availability of microwave and optical frequency standards at the highest level of accuracy is key to dissemination of high accuracy time and length services to UK science, technology and industry, and to international compatibility with other national measurement institutes and the BIPM through world-wide time transfer and clock comparison. Microwave atomic fountain standards, including the NMS Cs fountain standard, already play a key role in the derivation of UTC by means of Circular-T. Other newer microwave and optical atomic standards are evolving to the level of accuracy that enables their consideration as secondary representations of the second, with potential as candidates for a redefinition of the second in the longer term. The standards underpin the provision of traceability across a range of time, frequency, location and displacement services. Within this framework, the proposed activities have relevance across a number of sectors including microwave and optical instrumentation, aerospace, defence, communications, photonics, spectroscopy, fundamental physics and radioscience. In particular, a major technological driver is associated with ESA future requirements, through

the provision of state of the art clocks for future GNSS time provision, deep space networks and space missions with on-board clocks.

The metrology requirements identified during the formulation of this programme include:

- Consolidation of microwave fountain standards with state-of-the-art accuracies capable of contributing effectively to TAI and UTC via Circular-T, incorporation into an enhanced UK timescale able to play a major role in Galileo Time Service provision, and providing traceability to the SI second for emerging high-accuracy optical frequency standards.
- Development of optical frequency standards and optical clocks to reproducibilities beyond microwave limits, with a short-to-medium term view for their development as secondary representations of the second, as clocks for the local timescale, and in the longer term as candidates for a possible future redefinition of the second.
- Research and development to establish techniques for the worldwide comparison of optical frequency standards at the highest possible level of accuracy. This includes development of a transportable optical clock, capable of facilitating clock comparisons between national measurement institutes at levels of comparison accuracy better than that currently achievable with satellite time transfer techniques
- Simplification, automation and miniaturisation of optical clocks, to provide close-to-optimal clock instrumentation with extended/continuous operating cycles for application in GNSS ground stations or ESA deep space ground stations
- The application of different high-accuracy atomic frequency standards to tests of physics and fundamental constants and the search for their variation with time.
- Research and development to establish new measurement techniques and instrumentation evolving from leading-edge outputs of current optical frequency standards and metrology research.

## **Theme 2: Time scale realisation and dissemination**

Theme 2 is centred on the development and operation of the UK's national timescale UTC(NPL), related clock and time transfer applications, and time and frequency dissemination services. NPL provides a vital contribution to international timekeeping and to the development of high accuracy time and frequency transfer using both GNSS and two-way satellite transfer techniques. The operation of highly stable free running and steered timescales together with leading-edge time transfer systems are essential for the inter-comparisons of microwave and optical frequency standards with similar standards being developed at other NMIs. The expertise developed at NPL in developing algorithms for combining, predicting and steering clocks, and for combining time transfer methods, has found a demanding application in the development of the reference timescale for Galileo, the European Global Navigation Satellite System. NPL's algorithm designs have been applied to the development of both the Galileo Time Service Provider and one of the two Precise Timing Facilities. The work within this theme builds on strong collaborative links within the UK, notably with UCL on the development of GNSS time transfer analysis techniques and with Leeds University. The programme will be of significant value to UK users of time and frequency, and should also provide a unique timing contribution to the UK's GNSS community. NPL's MSF 60 kHz standard-frequency and time signal, the principal method of

time and frequency dissemination within the UK, will be maintained along with other dissemination services such as the NTP Internet Time Service.

The metrology requirements identified during the formulation of the programme include:

- Operate the UTC(NPL) timescale based on four active hydrogen masers and two commercial caesium clocks, including the incorporation of the fourth maser procured during the current Time Programme. Enhance the stability and uncertainty of the UTC(NPL) timescale through the evaluation and implementation of clock algorithms developed under the current Time Programme.
- The use of measurements from NPL's caesium fountain and other new frequency standards to enhance the timescale generated by the ensemble algorithm. The aim is to produce a free running NPL timescale and a steered UTC(NPL) timescale that are significantly more stable in the long-term (and maintained closer to UTC) than the current timescale based on a single active hydrogen maser.
- Operate and develop NPL's two TWSTFT earth stations, GPS hardware infrastructure and IGS station to ensure that NPL's TWSTFT and GNSS time transfer links continue to achieve a level of reliability, accuracy and stability at least equivalent to that of other leading NMIs.
- Development of clock and time transfer algorithms. In particular, the development of a time transfer algorithm producing a close-to-optimal composite time transfer link when supplied with individual GPS and TWSTFT time transfer measurements.
- Development of analysis techniques for international timekeeping. In particular the enhancement of NPL's international caesium fountain comparisons through the optimal use of NPL's ensemble timescale in interpolating and extrapolating caesium fountain data sets, and a formal analysis of the frequency uncertainties contributed by the time transfer links.
- Development of NPL's GNSS time and frequency capabilities. In particular the development of analytical techniques and implementation software to enable NPL to perform the highest quality GNSS time transfers both internationally and within the UK.
- Operation of the MSF standard-frequency and time signal. Ensure a smooth transition to the new operating contract at the end of March 2007, including an awareness campaign. Study of LF signal propagation, to understand better the consequences of relocating the MSF transmitter.
- Operation of other time and frequency dissemination services, including a GPS common-view service for high-accuracy applications and computer time services. Continuous monitoring of standard-frequency and time signals utilised in the UK, with the publication of the results in monthly bulletins. Provision of information services, enhanced www pages and e-mailed notices to subscribers.

### **Theme 3: Optical frequency dissemination**

The activities identified in this theme are key to the future provision of the SI units of time and length, and also to their dissemination to UK science, technology and industry. They play a vital underpinning role for the activities outlined in Theme 1, by providing a high accuracy means of comparing optical and microwave frequencies, and by seeking to establish high accuracy techniques for the comparison of optical frequency standards, both locally and remotely. They also provide traceability for dimensional metrology within the Engineering Measurement programme and for fundamental physics experiments being carried out within the Quantum Metrology programme. The proposed work builds upon existing frequency metrology infrastructure to provide enhanced traceability for a range of industrial requirements, and seeks to develop new measurement techniques and instrumentation to meet emerging challenges. The proposed activities have relevance across a number of sectors including optical instrumentation and precision engineering, aerospace, defence, optical communications, photonics, spectroscopy and fundamental physics.

The metrology requirements identified during the formulation of this programme include:

- High accuracy traceability of optical frequency standards to the SI second, in support of their development as secondary representations of the second, as clocks for the local timescale, and as candidates for a possible future redefinition of the second.
- Research and development to establish techniques for the worldwide comparison of optical frequency standards at the highest possible level of accuracy.
- Simplification, automation and miniaturisation of femtosecond optical frequency combs, for application in optical clocks (e.g. for GNSS ground stations or ESA deep space stations) and optical frequency calibration services, and to allow exploitation of the technology in applications beyond high precision frequency metrology.
- The development of very low phase noise microwave sources to support the development of primary frequency standards, faster comparison of optical and microwave standards, anticipated ESA ground station requirements and radar applications in the defence industry.
- Realisation and maintenance of the SI unit of length, the metre, in accordance with international definition, and in support of trade, quality assurance in industry, scientific innovation and instrumentation manufacture.
- Dissemination of optical frequency and the unit of length to UK industry, commerce, science and technology by provision of measurement services traceable to national standards, both directly to industry and indirectly through other second-level NMS services.
- Accurate, consistent and efficient measurement traceability for working optical standards across a range of spectral regions and diverse applications such as precision laser-based metrology and instrumentation, precision engineering, optical communications, high-resolution spectroscopy and fundamental physics.
- Research and development to establish new measurement techniques and instrumentation evolving from leading-edge outputs of current optical frequency standards and metrology research.

## **Programme development based on extensive consultation**

The content of the programme was defined during an extensive process of public consultation that included meetings, focus groups, targeted visits to companies and universities, road mapping exercises and Internet-based consultations. Key events in the consultation process are summarised briefly below.

### **Orientation**

The orientation meeting for the programme took place in central London on 5th July 2005. Representatives from industry, universities, government, regulatory bodies and the National Physical Laboratory identified new and emerging measurement requirements for the programme. Discussion centred on new developments in atomic frequency standards, GNSS, and frequency metrology. In each of these areas specific requirements for the new programme were identified. The agenda for the day, copies of the speakers presentations, and a report summarising the findings of the orientation meeting can be downloaded from the NPL web site at: <http://www.npl.co.uk/formulation/time/orientation.html>

### **Public consultation: first phase**

After the orientation meeting a period of public consultation began. This concentrated on public responses to the report of the orientation meeting, the identification of wide-ranging new measurement requirements, and the holding of focus groups on specific areas of science. The results of this process were summarised in a report that was made available to the Working Group at the beginning of January 2006 as one of the inputs to the pre-selection meeting that was held that month.

### **Pre-selection meeting, January 2006**

At the pre-selection meeting the Measurement Advisory Committee Working Group approved the new structure for the science themes in the programme and identified innovation priority areas within each theme. In the period from January 2006 to July 2006 NPL scientists developed specific scientific project proposals that addressed the innovation priority areas chosen by the Working Group and developed relationships with potential collaborators.

### **Public consultation: second phase**

A public consultation document was prepared following the January 2006 pre-selection meeting, to allow interested individuals, companies and universities to comment on the innovation priorities that had been identified by the Working Group. This was made available on the Internet from the following address:

<http://www.npl.co.uk/formulation/time/public.html>.

This web page also provided a form that interested parties could complete to submit their comments and suggestions. Of approximately 20 responses, most were from industry and academic representatives indicating an interest in collaborating in a particular topic area. All such offers were followed up by NPL scientists and the outcomes of those contacts have led to many of the collaborations that are included in the specific projects proposed for the new programme.

## Project Descriptions

### Project 1.1 Microwave frequency standards

#### *Project aim and objectives*

To provide the UK atomic fountain primary realisation and secondary representation of the SI second with leading-edge accuracy and enhanced frequency stability, able to contribute effectively to TAI and UTC, GNSS time service provision and absolute frequency referencing for optical standards.

The objectives of the project are:

- To operate and maintain the NPL primary frequency standard.
- To contribute to TAI, UTC(NPL) and optical frequency standard research.
- To complete rubidium fountain and publish results
- To improve accuracy and stability of primary caesium fountain frequency standard

#### *Background and rationale*

Modern timekeeping is an international undertaking. The global time standard is maintained by over 250 commercial caesium clocks operating in some 50 national time laboratories, with the data from these clocks processed by BIPM. The accuracy of the world time system is achieved by calibrating these commercial atomic clocks relative to primary frequency standards (PFS), devices designed to realise the SI second at the highest levels of accuracy.

The time standard is distributed to users either through terrestrial radio broadcasts (e.g. MSF signal in UK) or via a satellite navigation system (e.g. GPS or Galileo in future). The time signals are used in a number of applications from synchronising public clocks and telecommunication networks to facilitating calibration of frequency standards in electronics companies.

Microwave primary frequency standards form an essential part of the timing infrastructure by: a) providing traceability to the SI second, b) enabling characterisation of time scales (e.g. studies for provision of Galileo time), c) enhancing the work on optical frequency standards (e.g. evaluation of secondary representations of the second).

Frequency standards based on atomic fountain have been developed at NPL within the current and previous phases of the TFM Programme. A prototype caesium fountain NPL-CsF1 has been evaluated at the  $1.5 \times 10^{-15}$  level (combined uncertainty) and contributed to the steering process of the international time scale TAI. Work on the experimental fountain CsF2 and the Rb fountain has focused on research on new trapping and cooling methods in order to study and minimize frequency shifts related to atomic density. These shifts are currently one of the factors limiting the performance of the PFS.

### **Summary of technical work**

This project will develop and consolidate high accuracy microwave caesium and rubidium fountain standards accurate at the part in  $10^{15}$  level for realisation of the SI second. The caesium fountain facility F2 currently under development will be fully evaluated at a total uncertainty level of  $1.5 \times 10^{-15}$  or better, replacing the earlier F1 fountain as the primary facility for the realisation of the second. In this role, it will contribute to the steering of TAI on a regular basis via Circular-T, and provide the most accurate reference to the second for absolute measurement of optical frequencies. Finally, a rubidium fountain with high stability exceeding that of the caesium fountain will be optimised and evaluated to better than  $4 \times 10^{-16}$ , enabling its contribution to UK timescale and operation as a microwave secondary representation.

### **Deliverables**

<b>Project reference</b>	<b>Deliverable reference</b>	<b>Description</b>	<b>End date</b>
<b>EST0211</b>		<b>Project 1.1 - Microwave frequency standards</b>	
	EST021101	Publish an evaluation of Caesium fountain F2 targeting an accuracy of 1 part in $1E15$ and a stability of $1.5E-13$ at 1 second.	Sep-08
	EST021102	Maintain a Caesium fountain primary frequency standard, contributing to TAI at least 3 times during the programme and available as necessary for evaluating secondary representations and contributing to UTC(NPL).	Sep-09
	EST021103	Evaluate and submit for publication the performance of the Rb fountain.	Sep-08

## Project 1.2 Strontium ion optical frequency standard

### *Project aim and objectives*

To develop a fully evaluated single strontium ion optical frequency standard operating close to the quantum limit, with caesium-limited absolute frequency uncertainty, improved system reproducibility, and capable of contribution to TAI. To examine the potential of trapped ion systems to operate for extended periods without operator intervention as part of a transportable optical clock for intercomparisons, or for use in ESA ground stations.

The objectives of the project are:

- To develop an improved trapped ion optical frequency standard with target stability of better than 1 part in  $10^{15}$  at 100 seconds.
- To demonstrate a trapped strontium optical frequency standard with sufficient accuracy to contribute to the Circular –T dissemination of the international atomic timescale.
- Research and development into smaller integrated trapped ion frequency standards for future transportable optical clock applications.

### *Background and rationale*

Optical frequency standards based on narrow transitions in a number of trapped ions and atoms have recently demonstrated capabilities which are close to or better than microwave based standards. The strontium ion 674 nm transition was recently submitted by a CCL/CCTF<sup>1</sup> joint working group to the CCTF as a candidate for secondary representation of the second. In 2001 the transition was adopted as one of the radiations for realisation of the metre. The trapped strontium ion project in the NMS Length Programme resulted in the November 2004 publication in Science of the most accurately measured optical frequency standard at that time.

Ultra-stable optical frequency standards are of use to all those who need to measure time with the highest level of accuracy. With improved stability and accuracy at the leading edge, they will contribute to the international time scale. Another application is in space-based navigation systems, which depend on having very good clocks both on the ground, and in space. Initially optical frequency standards are likely to find application in ground stations for navigation systems. There are potential applications in both terrestrial navigation systems and the deep space network. Global navigation and tracking systems (eg GALILEO in Europe) are becoming increasingly important to commerce and society. Many areas of UK economy and infrastructure have come to rely on such systems and related markets are growing. The European Space Agency (ESA) is currently seeking to determine more widely which ground-based and space-based frequency metrology applications are most likely to benefit from optical clocks and frequency combs. In this respect the UK NMS is in a strong position to lead the development of optical frequency metrology. NPL is already leading two ESA studies on deep space ground-station optical clock possibilities and comb-based space-borne metrology, and has established collaborations with PTB, research institutes (Max Planck

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<sup>1</sup> Consultative Committee on Length/Consultative Committee on Time and Frequency

Garching, Observatoire Neuchatel), universities (eg Duesseldorf) and European time and frequency companies (eg Menlo GmbH, TimeTech GmbH) in this area, which we would expect to see strengthened during the programme.

Existing high-accuracy prototype optical frequency standards are complex research devices not yet suited for field use and transportation. In this respect, the development of stand-alone high-accuracy optical clock instrumentation capable of integration into deep space and GNSS ground stations, and as transportable frequency standards for international T&F comparisons, is seen as an emerging goal for both satellite navigation and international standards communities. The UK NMS is well placed to build on these developments, but significant metrology R&D is still needed in the short-to-medium term to enable the transition of these high-accuracy prototypes into stand-alone, high-reliability self-monitoring instrumentation.

### ***Summary of technical work***

This project involves the development of single cold trapped ion optical frequency standards with target stabilities and reproducibilities that will surpass current caesium fountain microwave capability. In particular quantum limited stability performance will be targeted, together with the assessment of systematic frequency shifts and uncertainties. This latter activity will be achieved to a level better than the caesium uncertainty, by means of two-trap comparisons. Another major activity will include design and implementation to achieve extended period operation of the standard necessary for e.g. extended contribution to circular-T.

Additionally a prototype ion trap breadboard will be set up to investigate and develop configurations for a small volume ion clock capable of stand-alone low-intervention operation. This will concentrate on developing a suitable trapped ion vacuum package / laser / ULE cavity interface capable of eventual integration into an optical clock instrumentation package. In the longer term further integration and simplification will be needed to address e.g. space-based optical clock requirements, but the issues addressed in this option will enable us to develop a transportable optical frequency standard for use in NMI intercomparisons and timing ground station applications.

## **Deliverables**

<b>Project reference</b>	<b>Deliverable reference</b>	<b>Description</b>	<b>End date</b>
<b>EST0212</b>		<b>Project 1.2 - Strontium ion optical frequency standard</b>	
	EST021201	An improved trapped ion optical frequency standard with target stability better than 1 part in 1E15 at 100 seconds and at least one contribution to TAI.	Sep-09
	EST021202	Demonstration of smaller integrated trapped ion prototype instrument components (including trap confinement systems and lasers) for future transportable optical clock applications in a 1 m <sup>3</sup> physics package.	Sep-09

## Project 1.3 Neutral lattice clock

### *Project aim and objectives*

To develop a capability in optical clocks based on large numbers of cold atoms confined within optical lattice trapping sites in order to contrast their potential for high stability and accuracy with trapped ion clock technology, with a long term perspective directed at a redefinition of the second.

The objectives of the project are:

- To develop a magneto-optical trapping facility to trap and cool neutral Sr or Yb atoms to temperatures in the  $\mu\text{K}$  range.
- To develop a high stability probe laser with low-drift sub-Hz linewidth capability.
- To develop lattice beam technology operating at the magic wavelength.
- To observe and preliminary characterise the mHz clock transition.

### *Background and rationale*

Over the past year, a number of absolute frequency measurements using caesium fountain referenced femtosecond combs of optical frequency standards based on various single trapped ion species have demonstrated accuracies at the Hz-level. These are close to the limiting frequency uncertainty of the caesium fountain primary standard, and future improvements are expected to deliver reduced uncertainties on the 3-5 year timescale.

An alternative technology under study for improved optical frequency standards is that of cold atom neutral lattice clocks. This relies on trapping a large number of cold atoms within an optical lattice, and offers the opportunity for very good frequency stability since this improves as the square root of the atom number. Additionally, there is good potential for high accuracy with this arrangement, provided each lattice trapping site is organised to hold no more than a single atom, and provided the laser forming the lattice trap is set to the “magic” wavelength where light shift effects are cancelled. Already, a number of NMIs and research institutes have begun investigations into cold Sr, Yb and Hg neutral lattice clocks, with most activity on strontium. Recently, first absolute frequency measurements in Japan and the US of the ultra-narrow clock transition in  $^{87}\text{Sr}$  in a 1-D lattice achieved frequency values that agreed at the  $2$  in  $10^{13}$  level. These initial measurements point the way to a significant new technology for optical frequency standards.

With the advent of trapped ion and cold atom optical frequency standards, it is likely that these will demonstrate improved reproducibilities over the microwave caesium fountain in the next few years. This raises the possibility for a redefinition of the second in a decade or so, and as a result a good deal of preparatory research is needed to fully evaluate the experimentally achievable uncertainties of the ion and atom options. At present, the major NMIs in this area include NIST, PTB and NPL. Currently NPL has no activity in cold atom optical standards. With the absence of such a developing capability, the UK NMS is likely to remain at a significant disadvantage over the next few years. This will be especially true if cold neutral lattice clock technology is able to reach its forecast potential in terms of stability

and accuracy. In this eventuality, the NMS / NPL could suffer a serious loss of influence within the international frequency standards community whilst it attempted to rapidly acquire optical lattice capability.

***Summary of technical work***

Development of a magneto-optical trapping and laser cooling facility to trap and cool neutral Sr or Yb atoms to temperatures in the  $\mu\text{K}$  range. As well as the development of a high-stability probe laser with low-drift sub-Hz linewidth capability. Also the lattice beam technology operating at the magic wavelength needs to be developed. There is potential for collaboration both between NPL and other NMIs, notably PTB and SYRTE, and between NPL and academic groups within the UK at Imperial, Oxford, Durham and Strathclyde.

**Deliverables**

<b>Project reference</b>	<b>Deliverable reference</b>	<b>Description</b>	<b>End date</b>
<b>EST0213</b>		<b>Project 1.3 - Neutral atom lattice clock</b>	
	EST021301	A demonstration of 2 stage cooling in a MOT to microkelvin temperatures with either Strontium or Ytterbium atoms.	Dec-08
	EST021302	A sub-Hz linewidth laser for probing the chosen atoms constructed and tested.	Sep-08
	EST021303	A demonstration of the ability to load the chosen atoms into a lattice trap.	Sep-09

## **Project 2.1 Time scale realisation and dissemination**

### ***Project aim and objectives***

To provide continuous operation, dissemination and development of the UTC(NPL) timescale which underpins MSF and other time and frequency dissemination services, GNSS (Galileo and GPS), and research and development of microwave and optical frequency standards.

The objectives of the project are:

- Maintenance and development of UTC(NPL) timescale and clock ensemble.
- To incorporate the NPL caesium fountain into UTC(NPL).
- Maintenance and development of the international and domestic satellite time transfer links which are a critical part of the NMS timing infrastructure and underpin future Galileo/GPS developments and applications.
- To operate, maintain and monitor the time and frequency dissemination facilities.

### ***Background and rationale***

This project is centred on the development and operation of the UK's national timescale UTC(NPL), related clock and time transfer applications, and time and frequency dissemination services. NPL provides a vital contribution to international timekeeping and to the development of high accuracy time and frequency transfer using both GNSS and two-way satellite transfer techniques. The operation of highly stable free running and steered timescales together with leading-edge time transfer systems are essential for the inter-comparisons of microwave and optical frequency standards with similar standards being developed at other NMIs. The expertise developed by the NMS in developing algorithms for combining, predicting and steering clocks, and for combining time transfer methods, has found a demanding application in the development of the reference timescale for Galileo, the European Global Navigation Satellite System. NPL's algorithm designs have been applied to the development of both the Galileo Time Service Provider and one of the two Precise Timing Facilities. The work within this theme builds on strong collaborative links within the UK, notably with UCL on the development of GNSS time transfer analysis techniques and with Leeds University. The programme will be of significant value to UK users of time and frequency, and should also provide a unique timing contribution to the UK's GNSS community. NPL's MSF 60 kHz standard-frequency and time signal, the principal method of time and frequency dissemination within the UK, will be maintained along with other dissemination services such as the NTP Internet Time Service.

### ***Summary of technical work***

This project consists of three parts. The first part will focus on the development of the UK national timescale UTC(NPL). The core requirement is to produce a UTC(NPL) timescale that is at least as stable and maintained as close to UTC as those of other European NMIs. The key to NPL's strategy is the maintenance of an ensemble of atomic clocks and measurement equipment that will permit NPL to become one of the "core" laboratories being paid to provide data to the Galileo Time Service Provider. The quality of NPL's clock

ensemble will be demonstrated both by the individual behaviour of the clocks and by the performance of UTC(NPL). An important part of this strategy is the commissioning of a fourth active hydrogen maser, to add redundancy to NPL's current "three cornered hat" of active hydrogen masers. The inclusion of caesium fountain measurements into the construction of UTC(NPL) will provide an opportunity to improve significantly the longer term performance of UTC(NPL). The current Galileo clock algorithm work has led to strong collaborations with Thales Research and Technology, Helios and Astrium within the UK, as well as Kayser-Threde, DLR and several European NMIs. The ensemble UTC(NPL) timescale resulting from this project will provide a world-class national timescale that can act as the highly stable and traceable link required by the atomic frequency standards development within NPL.

The second part will focus both on international time and frequency transfer methods and high accuracy GNSS timing applications within the UK. The aim of NPL's strategy is to develop both the TWSTFT and GNSS common-view time and frequency transfer techniques so that their performance is at least as good as that of any of the other major NMIs within Europe. This will give NPL a strong case for becoming one of the "core" laboratories contributing clock data to the Galileo Time Service Provider. NPL will continue to participate in international TWSTFT and GNSS calibration campaigns, joint development projects and working groups. NPL is already strongly represented on the TWSTFT working group and on several international committees, in particular a CCDS study group examining the international time transfer link configurations.

The last part of this project is concerned with the time and frequency dissemination services provided by NPL. A key aim is to ensure a smooth transition to the new operating contract at the end of March 2007, without disruption to the service. Monitoring of off-air standard-frequency and time signals, including MSF, Droitwich, and GPS, will continue, with publication of the results in monthly bulletins.

## Deliverables

Project reference	Deliverable reference	Description	End date
EST0221		<b>Project 2.1 - Time scale realisation and dissemination</b>	
	EST022101	Maintenance and development of UTC(NPL) including a free-running composite timescale and an enhanced UTC(NPL) with improved stability over periods greater than 5 days. A set of performance parameters will be updated and validated regularly and published on the NPL website.	Sep-09
	EST022102	Maintenance and development of the TWSTFT and GNSS time transfer links and infrastructure, including publication of their stability and uncertainties on the NPL website, implementation of new analysis techniques for GNSS carrier-phase time transfer and development of a combining algorithm for TWSTFT and GPS common-view data to deliver greater time transfer stability.	Sep-09
	EST022103	Dissemination of UTC(NPL) through direct services (radio broadcasts, NTP and telephone services), and the monitoring of other radio broadcasts (Droitwich 198 kHz and GPS) with monthly publication of the results on the NPL website.	Sep-09

## Project 3.1 Femtosecond optical frequency comb metrology

### *Project aim and objectives*

To provide high accuracy traceability from the SI second to optical frequency standards and dimensional metrology applications.

The objectives of the project are:

- To make absolute frequency measurements of trapped ion optical frequency standards relative to the SI second.
- To improve the stability and accuracy of the femtosecond comb facilities and to evaluate these improvements by comb comparisons.
- To increase automation of femtosecond comb operation, with the target of providing continuous monitoring of a test laser over a period of up to 24 hours.
- To demonstrate low noise microwave synthesis and transfer of frequency stability around the optical region of the spectrum.
- To implement a fully tested and evaluated transportable fibre-based femtosecond comb, capable of making GPS-referenced frequency measurements in both the visible region and the 1.5 micron optical communications band.
- An experimental study of potential applications of femtosecond comb technology in dimensional metrology
- To demonstrate rf and optical frequency transfer over installed optical fibre networks with a target stability of  $1 \times 10^{-14}$  at 1 second.

### *Background and rationale*

The activities identified in this project are key to the future provision of the SI units of time and length, and also to their dissemination to UK science, technology and industry. They play a vital underpinning role for the activities outlined in Theme 1, by providing a high accuracy means of comparing optical and microwave frequencies, and by seeking to establish high accuracy techniques for the comparison of optical frequency standards, both locally and remotely. They also provide traceability for dimensional metrology within the Engineering Measurement programme and for fundamental physics experiments being carried out within the Quantum Metrology programme. The proposed work builds upon existing frequency metrology infrastructure to provide enhanced traceability for a range of industrial requirements, and seeks to develop new measurement techniques and instrumentation to meet emerging challenges. The proposed activities have relevance across a number of sectors including optical instrumentation and precision engineering, aerospace, defence, optical communications, photonics, spectroscopy and fundamental physics.

### *Summary of technical work*

This project will use our femtosecond comb facility to provide high accuracy traceability of our optical standards to the SI second. The facility will be enhanced to provide improved stability and accuracy of optical-microwave and optical-optical comparison, to increase the degree of automation and to widen the spectral coverage. A transportable optical frequency comb will also be completed and evaluated, with the aim of exploiting the technology for

applications including low noise microwave synthesis and dimensional metrology. There is the potential for collaboration with Heriot-Watt University on several aspects of this project, for example by sponsorship of an Engineering doctoral student, whilst low noise microwave synthesis using combs will be explored in collaboration with ESL Defence Ltd. Miniaturisation and automation aspects will be informed by an ESA-funded study on optical synthesizers for space-borne optical frequency metrology, a collaborative project led by NPL which involves a number of European partners (Menlo Systems, Observatoire cantonal de Neuchâtel, Heinrich-Heine Universität Düsseldorf and Kayser-Threde).

The project also seeks to develop techniques whereby optical fibre networks can be used for the comparison of microwave and optical frequency standards at the highest possible level of accuracy. Initial work will be carried out in collaboration with the University of Essex, with the prospect for longer-term links between NMIs being pursued in collaboration with PTB and SYRTE.

## Deliverables

Project reference	Deliverable reference	Description	End date
<b>EST0231</b>		<b>Project 3.1 - Femtosecond optical frequency comb metrology</b>	
	EST023101	Absolute frequency measurements of trapped ion optical frequency standards relative to the SI second, with accuracies limited by the performance of the standards concerned.	Sep-09
	EST023102	Improvements to the stability and accuracy of the femtosecond comb facility, and an evaluation of these improvements by comb comparisons.	Sep-09
	EST023103	Increased automation of femtosecond comb operation, with the target of providing continuous monitoring of a test laser over a period of 24 hours.	Sep-09
	EST023104	Demonstration of low noise microwave synthesis and transfer of frequency stability around the optical region of the spectrum, by operation of femtosecond combs in optical clock mode.	Sep-09
	EST023105	Implementation of a fully tested and evaluated transportable fibre-based femtosecond comb, capable of making GPS-referenced frequency measurements in both the visible region and the 1.5 micrometre optical communications band.	Sep-07
	EST023106	Demonstration of rf and optical frequency transfer over fibre networks with a target stability of $1E-14$ at 1 s, including measurement of the effects of environmental factors, fibre amplifier noise and dispersion.	Sep-09

## Project 3.2 Frequency stabilised lasers for telecommunications and laser interferometer calibration services

### *Project aim and objectives*

To disseminate laser frequency and interferometer calibration services to telecommunications and dimensional metrology industry.

The objectives of the project are:

- To disseminate laser frequency and interferometer calibration services to telecommunications and dimensional metrology industry.

### *Background and rationale*

NPL currently calibrates around 30 frequency stabilised lasers and 17 laser interferometer systems annually. Around 5-10 laser systems are for customers within NPL, for example working on NMS programmes such as dimensional metrology, force (extensometry), pressure and photonics. External customers are, for example, in the defence and aerospace industries, and in precision instrument manufacturing. Within the last year, we have been also asked increasingly to provide traceability in the telecommunications industry via the calibration of frequency-stabilised lasers at 1550 nm. This project aims to maintain and develop these services that we offer, which are a key means to disseminate the metre to other teams within NPL and to industry.

### *Summary of technical work*

Various improvements to our current services are anticipated during the coming 3-year period – for example, software upgrades to allow us to deal more efficiently and flexibly with 1500-nm frequency stabilised lasers. We also intend to develop our own acetylene gas cell filling facility, in order to have direct control over parameters such as gas cell pressure and the level of impurities present, which affect the laser frequency at 1550 nm. Our laser interferometer facility also needs to be upgraded to allow us to deal with models that are new to the market.

In order to maintain our existing services, we need to continue the ongoing programme of calibrating the lasers (using our femtosecond comb system) and various air sensors used to determine the refractive index of air. This will allow us to maintain our UKAS accredited status for the laser frequency and interferometer calibration services.

## Deliverables

Project reference	Deliverable reference	Description	End date
EST0232		<b>Project 3.2 - Frequency Stabilised Lasers</b>	
	EST023201	Services for laser frequency and wavelength interferometer calibration maintained and developed, including continued UKAS accreditation. Developments to include an acetylene cell-filling capability, calibration software and procedures for 1550 nm stabilised laser calibrations, and a tuneable laser offset lock facility against a femtosecond comb.	Sep-09

## Project 4.1 Knowledge Transfer

### *Project aim and objectives*

- To stimulate awareness of the programme and facilitate the flow of knowledge from the components of the programme to the beneficiary community so that the impact is maximised.
- To engage with the beneficiary community to keep abreast of requirements for electromagnetic measurements and ensure that the programme responds accordingly.
- To obtain feedback on the uptake of the knowledge and report on the impact of the programme.

The overarching objective is to create a community of scientists, engineers, technicians, managers and leaders who can benefit directly or indirectly from the programme outputs and to engage with this community through mail shots and newsletters, and through holding relevant events, e.g. workshops, club meetings and training courses.

Activities will include:

- Trade and journal articles: Building on the history that NPL has for publishing articles in peer-reviewed journals, it is essential that these articles are passed on to the trade press in an appropriate format, for example as a case study.
- Newsletters
- Time & Frequency clubs
- Website: This needs constant review to ensure that it continues to provide any information that interested parties want and in format that is easily usable.
- External Partners: We will work closely with the relevant organisations (such as RIN and IET), industry and academia to identify and exploit synergies in knowledge transfer to maximise the outreach of the programme, this will include participating in the relevant committee activities of these organisations, for example the Professional Networks of the IET, Technical Committees of the IoP, and various Consultative Committees, to support the organisation of events, to contribute speakers to events, and to hold joint events.
- Managing and promoting the move of the MSF transmission from Rugby to Anthorn

### *Background and rationale*

Coordinated Universal time (UTC) forms the basis of civil time keeping around the world today. The seconds of UTC are explicitly related to the SI definition of the second and hence, as well as being the internationally agreed basis for the time-of-day, UTC is also the primary mechanism for disseminating the measurement standards of time interval and frequency. As such, all our time measurements from the most precise to the most mundane are locked together. The fact that UTC is used to disseminate the SI second explains why the maintenance of the national time scale is funded by the NMS. It also explains why the audience for the NMS TFM Programme is rather different from that for other NMS Programmes. As well as specialists concerned with accurate measurement, the Programme attracts interest from many non-specialists seeking general information on how time keeping is carried out today.

The information required by specialists will often be found in specific technical projects within the Programme, with the Knowledge Transfer project guiding the newcomer to the most appropriate source for that information. The current project also provides a point of contact for the generalist who needs background information on time keeping. During the current NMS TFM Programme, direct access to details of the programme has been available through an advice service accepting enquiries by telephone, letter, fax or e-mail, a website, newsletters and a club. The advice service is available to answer the entire range of questions, from the dates for British Summer Time to technical details about the maintenance of the national time scale. This one-stop shop for information from the programme receives several hundred enquiries each year. The advice line, operated by NPL, is one of the main pillars supporting Knowledge Transfer in the Programme.

As well as the ongoing advice service there is a need to educate and inform both key users of the MSF service and the public about the move of the transmitter from BT in Rugby to VT Communications in Anthorn. In the current programme there has already been a high profile Knowledge Transfer project to raise awareness of this move and ensure that users who need MSF for critical systems (Network Rail, NATS) know about it and are in contact with us. This will mean that we will be better able to keep them informed of the testing and switchover as it proceeds in turn making sure that the transition is smooth and gives NPL positive exposure. Knowledge Transfer is also using the opportunity to re-brand MSF as “The Time from NPL” and, it will continue to work with radio-controlled clock manufacturers to raise the public awareness of the link between NPL and MSF.

***Summary of work***

The overarching KT theme links to all technical projects within the programme. This close linkage will provide support for the KT of individual projects as well as the supply of knowledge ensuring effective exploitation through this theme. Constant communication will ensure that the entire NMS TFM Programme is available for dissemination to as wide an audience as possible. If people have access to information about the NMS TFM programme, it can increase the amount of potential collaboration on other projects.

**Deliverables**

<b>Project reference</b>	<b>Deliverable reference</b>	<b>Description</b>	<b>End date</b>
<b>EST0241</b>		<b>Project 4.1 - Knowledge Transfer</b>	
	EST024101	Areas of the NPL website relevant to the programme maintained and developed, including a new area related to the move of MSF from Rugby to Anthorn providing information to users about the changes and the opportunity for them to report reception issues.	Sep-09
	EST024102	At least 18 general interest articles relevant to the programme published in trade journals, NPL newsletters (including electronic newsletters), the general press, or through strategic partners.	Sep-09
	EST024103	At least 18 presentations relevant to the programme at NPL Club meetings or similar events organised through strategic partnerships with other organisations.	Sep-09

## **Projects 5.1 & 5.2 Programme management and Formulation**

### ***Project aim and objectives***

The aim of this project is to ensure effective coordination of the Time, Frequency & The Metre Programme across all projects so that the Programme delivers maximum benefit to the UK. In addition, this project has the aim to produce a proposal of work for the next TFM Programme through consultation with industry, regulators and other end users in order to determine future measurement requirements or other issues that need to be addressed.

The objectives of the project are:

- To ensure cost-effective delivery of the Programme.
- To coordinate activities between TFM and other NMS Programmes.
- To provide reports on progress on a monthly and annual basis.
- To conduct a wide ranging consultation exercise with industry, regulators, government and other end users to determine current and future measurement requirements.
- To draw together all inputs received during formulation into a new Programme of work that will form the next TFM Programme.

### ***Background and rationale***

The Time, Frequency & The Metre Programme consists of a number of projects whose delivery is dependent on efficient use of resources and facilities. The complexity of the technical and knowledge transfer activities will require close monitoring of progress and a flexible approach to resourcing. This project coordinates activities in the Programme to ensure that all milestones are completed in a timely and cost-effective manner and that all reporting requirements to the DTI and its advisors are met.

As the UK economy evolves and technology trends develop, new measurement requirements emerge. To underpin growth in the economy these measurement requirements must be successfully addressed as early as possible. In order to determine the present and future measurement requirements of industry, regulators, government and other end users, it is important that their views are sort through a wide ranging consultation process. This process includes looking at independent evidence of measurement needs as expressed in government reports, foresight activities, industry roadmaps etc. as well as conducting meetings, surveys and interviews focusing on specific topics of interest. Collation and assessment of information from all sources enables a list of activities to address the measurement needs to be formulated. An independent prioritisation of these activities enables the optimum programme of work to be developed which will maximise the impact of available funding on UK measurement requirements.

### ***Summary of work***

This project will provide the overall co-ordination for the NMS Time, Frequency & The Metre Programme 2006-2009. Reports on progress will be provided monthly along with invoices to the DTI. On each anniversary of the start of the Programme an annual report on progress will be provided for the TFM working group as well as the DTI.

This project will ensure the successful formulation of the 2009-2012 Time, Frequency & The Metre Programme through staging a wide-ranging consultation exercise with key end-users in UK industry, government and other bodies.

The direction and strategy of the Programme will be determined by a ‘trend spotting forward look’ review of measurement requirements and a subsequent Orientation meeting. Technical projects will then be developed and presented to the TFM Working Group at its Annual Review. After the scope of the Programme has been focussed further, the remaining portfolio of projects will be presented for public comment before being prioritised by the Working Group. The projects selected by the prioritisation process will comprise the final Programme, which will developed into a form suitable for ministerial approval before commencement of the technical work of the Programme in October 2009.

## Deliverables

Project reference	Deliverable reference	Description	End date
<b>EST0251</b>		<b>Project 5.1 - Programme management</b>	
	EST025101	Delivery of the programme on time and to budget, through the effective management and coordination of all projects carried out by NPL. This will include promotion of the programme objectives, coordination with other programmes, regular updating of the National Measurement Facilities Database and preparation for and hosting of Annual Reviews.	Sep-09
	EST025102	Monthly progress and financial reports to NMSD, in agreed formats.	Sep-09
	EST025103	Extended annual progress reports to NMSD, highlighting achievements and problems, reporting key performance metrics and recommending any necessary Programme modification. These will incorporate a commentary on the potential for European collaborative R&D, joint use of facilities and more specialisation / devolution in provision of measurement services.	Sep-09
<b>EST0252</b>		<b>Project 5.2 - Programme formulation</b>	
	EST025201	Support to the formulation of following programmes in the new structure by whatever process is agreed.	Sep-09