# The National Measurement System Programme for Time Metrology October 2003 to September 2006

Formulated on behalf of the
National Measurement System Directorate
of the Department of Trade and Industry

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**CONTENTS**

# SECTION 1: INTRODUCTION

## This Document

This document describes the National Measurement System (NMS) programme for Time Metrology for the period from October 2003 to September 2006. It describes both the overall objectives and organisation of the programme, and the projects and deliverables. The first section of the document provides background information on the Programme, both in terms of describing the National Measurement System of which it is a part, and in terms of the context for time and frequency measurement in the UK and abroad. The second section describes the themes and projects for the programme. More detailed project and sub-project descriptions are provided in Annex C.

## The National Measurement System

The UK National Measurement System (NMS) is the national framework within which organisations such as the National Physical Laboratory establish primary standards of measurement (for mass, length, time, electrical quantities etc.) which are then rigorously linked to practical measurements in industry and commerce, government agencies, local government, hospitals and research by an unbroken chain of measurement comparisons all having stated uncertainties. In formal terms, it is the infrastructure ensuring that measurement in the UK is valid, fit for purpose, and internationally recognised.

The DTI National Measurement System Directorate (NMSD) is responsible for securing the objectives of the NMS, through publicly-funded programmes of work in which it acts as a customer on behalf of a wide range of ultimate beneficiaries in the UK, and through further development and interpretation of underlying Government Policy. The top-level objectives of the NMS are to facilitate free trade, to promote industrial competitiveness, and to meet statutory and regulatory obligations. The NMSD seeks to address these objectives by providing an effective and comprehensive National Measurement System for industry, and acting as the centre within Government for policy on measurement standards for industrial, commercial, environmental, healthcare and regulatory use.

## The Context for the NMS Time Programme

The global time standard is Co-ordinated Universal Time (UTC - *see notes in Annex A for more background information*). 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.

The diagram on the adjacent page shows the process for generating UTC each month, including two key steps in the process that have not been mentioned so far. The stages in producing UTC can be summarised as follows:

- Data from over 200 atomic clocks is used to compute an extremely stable time scale, referred to as *Echelle Atomique Libre* (EAL). While EAL is very stable, the duration of the EAL scale interval is not constrained to agree with the SI definition of the second.

- Data from a small number of primary frequency standards is used to calibrate EAL, and produce *International Atomic Time* (TAI).

- The civil time standard is *Coordinated Universal Time* (UTC), which is defined to be TAI offset by an integer number of seconds. The exact offset is chosen so that UTC remains in approximate agreement with *Universal Time* (UT), or equivalently, Greenwich Mean Time (GMT). The International Earth Rotation Service (IERS) compares UT and UTC and issues instructions if a new offset is required.

- The BIPM publishes the Circular T each month listing the difference between UTC and UTC(k) at five day intervals for each contributing laboratory. The laboratories can choose to adjust their reference clocks to steer towards the UTC standard, knowing that the primary frequency standards ultimately set the rate for UTC.

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 Programme.

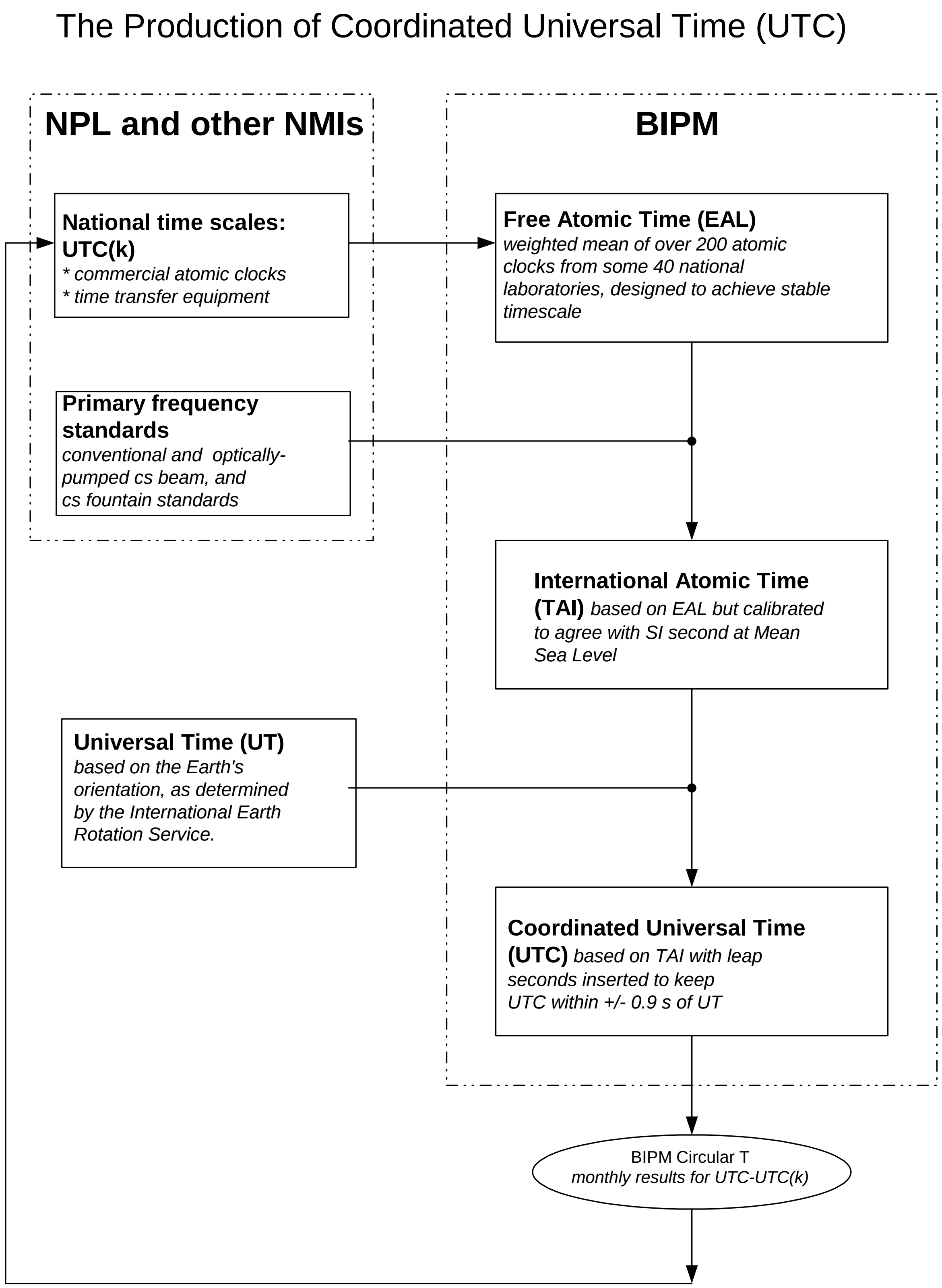


***FIGURE 1***

*The diagram indicates the various contributions needed to generate International Atomic Time (TAI) and Co-ordinated Universal Time (UTC)*

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.

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.

The discussion above describes the general background to the NMS Time Metrology Programme. However, in addition, there are three specific issues that have strongly influenced the strategic directions proposed for the next programme.

(i) **Quantum Frequency Standards:**
The caesium fountain is the most advanced form of primary frequency standard today. The best standards are *accurate* to 100 picoseconds over a day, comparable to the *stability* of the best commercial atomic clocks (i.e. active hydrogen masers) and time transfer methods (i.e. TWSTFT and Geodetic GPS time transfer). The net effect is that no component (primary frequency standard, time scales, time transfer links) dominates the performance of the international time system today. However, the conventional wisdom is that primary frequency standards will improve further, putting the commercial atomic clocks and time transfer links as the limits on time scale performance. This change of limiting factors has stimulated a stronger emphasis on applying time scale algorithms to improve the performance of the existing facilities in the UTC(NPL) time scale. It has also stimulated a number of sub-projects to push forward improvements in time transfer technology to support the intercomparison of primary frequency standards between different national measurement institutes.

The other important development over the last three years has been the introduction of very stable femto-second frequency combs that are able to span optical to microwave frequencies. The promise of optical frequency standards based on trapped ions has been recognised for a number of years. The frequency comb makes it much easier to conduct direct comparisons of optical and microwave standards, and has enabled the demonstration of an all-optical atomic clock (i.e. the optical frequency is in effect down-converted to a lower frequency where conventional electronics can generate RF frequencies and 1 pulse per second output). NPL has significant strengths in optical frequency metrology, and this programme is proposing to support the interface between the current (microwave) primary frequency standard and the new optical frequency standards that are being developed in other NMS Programmes.

(ii) **GPS and Galileo**:
The Global Navigation Satellite System is a generic name for a number of satellite navigation systems either in operation or under development. GPS is probably the best known, and it has already transformed the timing industry because of its global coverage, its tremendous accuracy, and the low cost of GPS receivers. The investment in follow-on systems such as EGNOS and Galileo indicates that GNSS will be a major part of the time infrastructure for the foreseeable future. The obvious direction for the NMS is to support GNSS users by providing services to validate GNSS signals and GNSS timing equipment. The key product that the NMS Time Programme can offer is a stable, accurate and independent time scale against which to validate GNSS. The validation role can be used both to help introduce new technologies to the market place (supporting innovation in the UK) and to provide assurance for technologies already accepted by the market.

In addition, there is a European initiative known as Galileo to develop a global navigation satellite system. Galileo has the potential to deliver standard time from European sources to a global user base. However, the European timing infrastructure is designed to meet national priorities and not for GNSS timing services. This programme proposes a number of modest initiatives to help reconfigure the national infrastructure to meet Galileo requirements. The proposals build on existing facilities for supporting UTC.

(iii) **MSF:**
The current contract for the broadcast of the MSF time signal expires in 2007. As such, preparations for the future of the MSF service form a crucial aspect of activities in the next Programme.

**Programme Objectives**

Having described the context for the NMS Time Programme above, it may help to summarise its top-level objectives as follows:

- 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 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.

# SECTION 2: THE PROPOSED NMS TIME PROGRAMME

## OVERVIEW

The proposed NMS Time Programme has been divided into two technical Themes, with two additional Themes to cover knowledge transfer and programme management activities. Those Themes are:

- **Theme 1**: Standards for international time scales
- **Theme 2**: Dissemination of time and frequency standards in the UK
- **Theme 3**: Knowledge transfer
- **Theme 4**: Programme management and development

Theme 1 underpins the whole Programme by providing access both to the SI second and to the global time standard, Coordinated Universal Time scale (UTC). Theme 2 provides the main delivery mechanisms for the time and frequency standards maintained in Theme 1, making them available to the wider NMS. Theme 3 coordinates the various knowledge transfer activities throughout the Programme, and acts as a focal point for more general knowledge transfer activities.

The detailed objectives and deliverables for each Theme are described in the remainder of this document.

## THEME 1: Standards for International Time Scales

### Introduction

The projects in this Theme are directed towards the maintenance and development of International Atomic Time (TAI) and Coordinated Universal Time (UTC).

There are a several time scales in use today for a variety of scientific and technical applications in astronomy, geodesy, and satellite navigation as well as for civil purposes. International Atomic Time (TAI) is maintained by the international metrology community and it is based explicitly on the SI definition of the second *(see box below)*.

> **The SI second**
> The SI unit of time, the second (s), was defined in 1967 by the 13th General Conference of Weights and Measures in the following terms:
>
> *"The second is the duration of **9 192 631 770** periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom."*
>
> The SI derived unit of frequency is the hertz, Hz.

TAI is maintained by over 200 atomic clocks in some forty national time laboratories around the world. The large number of clocks contributes to the stability of the time scale, while the large number of laboratories provides both redundancy (vital in a time scale that underpins so many applications) and greater accessibility to the standard. Currently, the National Physical Laboratory hosts the UK's contribution to TAI on behalf of the NMS. Most of the clocks in the system are commercial devices that have good stability but only limited intrinsic accuracy. The system as a whole is calibrated by a small number of primary frequency standards. In 1998, just six primary standards in four laboratories provided measurements adequate for calibrating TAI.

Coordinated Universal Time (UTC) is based on TAI, but offset by an integer number of seconds so that it remains in approximate agreement with more traditional time scales based on the Earth's rotation (i.e. Universal Time or, equivalently, Greenwich Mean Time). There is no natural gearing between TAI and GMT and so additional 'leap seconds' are applied when required to keep UTC in agreement with GMT to the nearest 0.9 seconds (*see notes on time scales in Annex A for background information*). UTC is the global standard for civil-time keeping today. It provides the most stable time base available because it is based on TAI, but also acts as a good approximation to its antecedent, GMT, for everyday purposes.

In contributing to TAI and UTC, the UK has direct access both to the global standard for civil timekeeping and to the internationally accepted standards for realising the SI second. As such, the three projects in this Theme provide the foundation stones of the NMS Time Programme. They mirror the key components of the international time system: time scales, time transfer links, and primary frequency standards.

While this Theme is directed towards the UK's contributions to the international time system, the mechanisms for disseminating those standards in the UK are mostly addressed within Theme 2.

The projects in this Theme are:

***Project T11 :***
**THE MAINTENANCE AND DEVELOPMENT OF UTC(NPL)**

The objectives of this project are to support the operation and development of the international civil time scale, Coordinated Universal Time (UTC), in partnership with the BIPM and the national time standards laboratories from other countries around the world; and to provide a reference time standard for the UK that is traceable to the international civil time scale, Coordinated Universal Time (UTC).

Its main deliverable is UTC(NPL), a continuously operating national time scale that is traceable to the international civil time scale, Coordinated Universal Time (UTC), with the uncertainty in the UTC-UTC(NPL) offsets published in the BIPM Circular T to be established with an uncertainty of ± 5 ns (1σ) or better.

***Project T12:***
**ALGORITHMS AND ANALYSIS**

The objectives of this project are to extract the best possible performance from the UTC(NPL) time scale and time transfer links by developing and applying appropriate combining algorithms and analysis techniques. Its main deliverables are fundamental studies of time and frequency data analysis techniques; a timescale algorithm for UTC(NPL); and operational algorithms for the UTC(NPL) time scale and for steering atomic time scales to UTC. We anticipate at least two high quality publications in refereed journals on aspects of the above work.

***Project T13 :***
**DEVELOPMENT OF GNSS TIME TRANSFER**

The objective of this project is to assess and prioritise the GNSS time transfer techniques that can be applied for time metrology. The project will carry out an assessment of GNSS time transfer methods (to include high-level options, current best-practice, fundamental limits, data transfer/processing issues, new signals and technology developments) with recommendations on further experimental studies to be pursued as part of the project. These investigations will conclude with a cost-benefit analysis of the high-level GNSS time transfer options, with recommendations and implementation plans for options to be taken forward within the NMS Time Programme.

***Project T14 :***
**PRIMARY FREQUENCY STANDARDS**

The objective of this project is to realise the SI second at the highest levels of accuracy and to relate those measurements to International Atomic Time (TAI) and to support developments across the National Measurement System to link the primary standards of time and length. Its main deliverable is a primary frequency standard contributing to TAI in each year of the Programme.

***Project T15 :***
**SECONDARY REPRESENTATION OF THE SI SECOND**

The objective of this project is to provide an ultra-high stability microwave frequency standard to underpin the noise analysis of the primary standards of time and length. Its main deliverable will be a high-flux rubidium-87 fountain with a cryogenic sapphire-ring resonator with a target frequency stability of 5 parts in $10^{14}$ at one second averaging time and 5 parts in $10^{15}$ at 100 seconds averaging time**.**

***Project T16:***
**<u>INTERNATIONAL COORDINATION AND REPRESENTATION</u>**

The objectives of this project are to represent UK interests on the international committees with primary responsibility for maintaining and disseminating civil time standards. Its main deliverables are UK representation at the following international committees with primary responsibility for maintaining and disseminating civil time standards: Consultative Committee for Time & Frequency (CCTF); International Telecommunications Union Radiocommunications Sector (ITU-R) Working Party 7A and the EUROMET Technical Committee for Time & Frequency.

## THEME 2: Dissemination of time and frequency standards in the UK

### Introduction

The projects in Theme 2 are directed towards the dissemination of time and frequency standards to the NMS, and to the wider user community in the UK. Hence, the activities in Theme 2 can be seen as the primary delivery mechanism for the time standards being maintained and developed in Theme 1.

Three generic approaches are adopted here for the dissemination of time and frequency standards. One approach is the direct broadcast of standard-frequency and time signals based on a national standard. The MSF 60 kHz and NPL telephone time services are examples of the broadcast method. The second approach is to monitor a third party signal and confirm that it meets its stated specification. A calibration laboratory using the MSF bulletins for integrity checks would be an example of this second approach. The third approach is an extension of the second, where the national time standard is used to apply differential corrections to achieve a more accurate time or frequency measurement than would be possible using the broadcast signal alone. Then the broadcast signal simply becomes a transfer standard to give remote access to the national time standard. Actively broadcasting a standard-frequency and time signal can be considerably more expensive than passively monitoring a third party signal, but has the advantage that the NMS can guarantee that there will be at least one reliable source of Coordinated Universal Time (UTC) in the UK. In contrast, the 'monitoring' route is a very cost effective way of disseminating national standards of time and frequency, but inevitably there is a lack of direct NMS control.

The time and frequency dissemination activities are important because precise time keeping and frequency measurement underpin a wide range of industrial activities in the UK. Direct users of high-accuracy and traceable time and frequency include the growing number of UK-based companies that manufacture receivers and other equipment for satellite-based navigation systems and telecommunications networks. There is also a wide but largely hidden user base which makes use of the MSF 60 kHz radio time signal to provide time with lower accuracy but traceable to UTC(NPL). In addition, an increasingly important dissemination route for computing equipment is the NTP server, providing time synchronisation via the Internet. With the growth in e-commerce, it is likely that telephone and Internet services will increase in importance.

Finally, the current contract for the broadcast of the MSF time signal expires in 2007. As such, preparations for the future of the MSF service form a crucial aspect of activities in the next Programme.

The projects in this Theme are:

***Project T21 :***
**<u>MSF STANDARD-FREQUENCY AND TIME BROADCAST</u>**

The objectives of this project are to support the operation and future development of the MSF standard-frequency and time signal.

Its main deliverables are:

- The MSF 60 kHz Standard Time and Frequency Signal itself.

- An MSF Information Service providing background information and status reports for MSF users

- A new contract for the broadcast of the MSF 60 kHz signal beyond March 2007, and an associated Awareness Campaign to keep MSF users informed of developments.

***The Future of the MSF Service***

*The current broadcast contract with BT runs until 31 March 2007 after which new arrangements will need to be in place if the MSF service is to continue. As such, in addition to the specific deliverables identified above, there will be a set of ongoing activities related to the long-term future of the MSF service. The MSF Information Service will provide news and information on these developments to end-users throughout the course of the programme.*

***Project T22 :***
**MONITORING OFF-AIR TIME AND FREQUENCY SIGNALS**

The objectives of this project are to validate the time and frequency radio signals most commonly used in the UK, and where appropriate to provide regular information that allows a user to demonstrate traceability from one of the signals to the UK national time scale UTC(NPL).

The following deliverables will be provided for the GPS, MSF 60 kHz and Droitwich 198 kHz standard-frequency and time signals:

- Monthly bulletins reporting the accuracy and integrity of those signals to be published in print and on the Internet.

- User Guides describing how the Bulletins can be used with each standard-frequency and time signal to provide the user with accurate and reliable time and frequency measurement standards.

***Project T23 :***
**COMPUTER TIME SERVICES**

The objectives of this project are to provide access to the UK national time standard via telephone and the Internet. Its main deliverables are a telephone time service and an Internet (NTP) time service, both supported by User Guides.

## THEME 3: Knowledge Transfer

### Introduction

Knowledge transfer activities are found in nearly every project within the NMS Time Programme, typically in the form of measurement services or user guides. The sole project in this Theme is designed to coordinate the various knowledge transfer elements of the Programme and make them accessible as a coherent whole. To this end, information on the NMS Time Programme will be made publicly available, and opportunities will be provided for UK industry to comment on and contribute to the Programme. The sole Project capturing these activities is:

***Project T31:***
**KNOWLEDGE TRANSFER**

The objectives of this project are to promote the NMS Time Programme and its key outputs to UK industry; to provide general information and advice on Time metrology matters for users in the UK; to support dialogue between the NMS Programme and UK timing specialists, and to work with those specialists to promote best-practice among the wider user community in the UK; to respond to new issues and concerns for the timing community as they arise during the course of the Programme; and to ensure best practice is developed and used in all aspects of knowledge exploitation within the Programme. Its main deliverables are:

- An Awareness Strategy and Campaign for the NMS Time Programme

  The objective of making the programme available and accessible to UK industry will be supported by a formal awareness strategy, to be developed in the first six months of the Programme. The subsequent awareness campaign will expose and promote the programme to a wider audience, for example, by exploiting the knowledge transfer potential of partnerships with like-minded programmes and professional bodies such as the Pinpoint Faraday Partnership, the Institution of Electrical Engineers (IEE), and the Institute of Physics (IoP).

- An NMS Time Metrology Information and Advice Service

  An advice service accepting enquiries by telephone, letter, E-mail or fax to answer queries received in relation to time and frequency issues in the UK The Information and Advice service is supported by web pages with answers to frequently asked questions, details on research carried out as part of the Programme and links to relevant external projects.

- NMS Time & Frequency User Club

  To provide a forum for communication and information exchange on timing issues in the UK. To facilitate dialogue between the NMS Time Programme and the community of timing specialists in the UK. To support those timing specialists in promoting best-practice amongst their own user communities. The Club will operate five meetings and circulate five newsletters over the course of the Programme.

- Impact measures

  To measure and record the impact of the Programme in a structured manner and use this information to ensure effective knowledge transfer across the whole Programme.
  Details of impact assessment will be included in annual reporting to the DTI.

**THEME 4: Programme management and future programme development**

There are two projects in this Theme, one (T41) for Programme Management and the other (T42) for Future Programme Development. Their combined objectives are:

- To manage the delivery of the whole programme and to ensure that objectives are met within time and budget.

- To inform the NMSD of progress in delivering the agreed Programme and of any issues affecting the delivery or future direction of the Programme.

- To assist the DTI in the identification and procurement of the most effective programme of work for the available budget, consistent with the agreed objectives of the NMS Programme.

# ANNEX A: NOTES ON TIME SCALES

The following notes identify the key events in time-keeping from the adoption of Greenwich Mean Time as the global standard in 1884 to the present day.

**Before GMT**
The position of the sun in the sky has been used as a basis for measuring time for many centuries. One simple example is that 12 noon in local solar time occurs when the sun is directly `overhead'. However, local solar time does not provide as uniform a time scale as that based more implicitly on the rotation of the Earth about its axis. The Earth's orbit is elliptical and its axis tilted, so that the actual position of the sun against the background of stars appears a little ahead or behind the expected position. The accumulated error varies from 14 minutes slow in February to 16 minutes fast in November. These effects can be predicted, and a more uniform time scale can be established on the basis of a hypothetical 'mean' sun that moves with uniform speed across the sky. This form of time scale is known as mean solar time. The mathematical formula to convert local solar time into local mean solar time is known as *the equation of time*.

A sundial measuring the local mean solar time was the fundamental basis for time-keeping in most towns and cities at the beginning of the nineteenth century. As such, the local time varied by 4 minutes for each degree of longitude around the world.

**Greenwich Mean Time (GMT)**
The geographical expansion in communications brought about by the railways during the nineteenth century created a need for first national, and then international, conventions on time-keeping. Agreement on a global standard was first achieved at the International Meridian Conference held in Washington in 1884. The Conference established the Royal Observatory at Greenwich as the reference for the world’s prime meridian and GMT as the basis for the universal day. Greenwich was a viable candidate because of the quality of the work carried out at the Royal Observatory. However, a key factor in Greenwich finally being chosen was the fact that 70% of the world’s shipping used charts prepared by the Admiralty using a datum at the Greenwich Meridian.

**Universal Time (UT)**
In 1928, the International Astronomical Union adopted the term *Universal Time* for the GMT day beginning at Greenwich Mean Midnight. The reason for the innovation was that the astronomical day had traditionally started at noon, while the civil day started at midnight. In scientific circles, the term Universal Time (UT) avoided the confusion over the start-of-day associated with GMT.

**International Atomic Time (TAI)**
Caesium atomic clocks were developed at the National Bureau of Standards in the USA and the National Physical Laboratory in the UK in the mid-1950’s. For the first time, a man-made device was able to keep time more regularly than was possible using astronomical observations.

From 1955 to 1958, an experiment was conducted by the National Physical Laboratory (NPL), and the United States Naval Observatory (USNO), to calibrate the new atomic time standards. NPL had the world’s first caesium atomic clock while the USNO had the world’s most accurate astronomical time keeping capability. The SI second was redefined in terms of the caesium atom in 1967 on the basis of the NPL/USNO experiment.

Since the late 1950's, atomic clocks in a number of different countries have been used to keep what has now become International Atomic Time (TAI). Note that TAI was set to agree with Universal Time (UT) at the start of 1958, but has kept time independently since then. TAI is much more stable than UT (by a factor of a million today) and many technologies depend ultimately on TAI rather than UT. For example, the clock rates specified in today's digital telecommunications networks are a factor of 3000 more stable than UT. In contrast, the advantage of UT over TAI is that it is geared to the rotation of the Earth and hence is directly related to our concepts of night and day.

**Coordinated Universal Time (UTC)**
A new time scale called Coordinated Universal Time (UTC) was adopted as a global time standard in 1972.

UTC is a compromise time scale that offers the accuracy and stability of TAI while staying in approximate agreement with UT. It is based on TAI but offset by an integer number of seconds. For example, in October 2003, TAI was exactly 32 seconds ahead of UTC. Since the current system was established in 1972, TAI (and hence UTC) have been running ahead of UT. The UTC time scale allows for leap second adjustments to be made to keep it in agreement with UT to the nearest 0.9 seconds. Note that the effect of a leap second is identical to setting UTC forwards or backwards by one second. For example, UTC might change from being 0.6 seconds ahead of UT to being 0.4 seconds behind after a leap second has been introduced.

Today, TAI and UTC are maintained by over 200 atomic clocks in some 40 time standards laboratories around the world. The Bureau International des Poids et Mesures (BIPM) is responsible for computing TAI and UTC on the basis of data from those laboratories. UT is maintained by the International Earth Rotation Service (IERS) and it is they who decide when leap second adjustments should be applied. The procedures for maintaining UTC are described by an International Telecommunications Recommendation (ITU-R Recommendation TF.460).

**Access to the time**
Accurate time is made available to the public and industry by radio broadcasts and telephone links. For example, the Global Positioning System (GPS) broadcasts accurate UTC time information (derived from the clocks at the US Naval Observatory) around the globe. There are a number of terrestrial radio broadcasts dedicated to time, each deriving UTC from one of the forty international time laboratories (e.g. MSF on 60 kHz from NPL in the UK, DCF77 on 77.5 kHz from PTB in Germany, WWVB on 60 kHz from NIST in the USA, etc.). In addition to radio broadcasts, there are often direct telephone and Internet links to the time laboratories.

Often, time will be delivered to the eventual user through a number of stages. For example, from a UK perspective, the BT speaking clock derives its time from the MSF 60 kHz time signal, which in turn derives its time from the National Physical Laboratory. The BBC's Greenwich Time pips derive their time jointly from MSF (i.e. from the National Physical Laboratory) and from GPS (i.e. from the US Naval Observatory). On the Internet, the Network Time Protocol is widely used to distribute time to servers, and it is possible to establish reliable links back to UTC in this way.

## ANNEX B: ABBREVIATIONS

| | |
|---|---|
| BNSC | British National Space Centre |
| BIPM | International Bureau of Weights and Measures |
| BT | British Telecommunicatons plc |
| CCTF | Consultative Committee on Time and Frequency |
| CIPM | Comité International des Poids et Mesures |
| DTI | Department of Trade and Industry |
| EAL | Free Atomic Time |
| EGNOS | European Geostationary Navigation Overlay System |
| ESA | European Space Agency |
| EUROMET | European Metrology Network |
| GMT | Greenwich Mean Time |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| ITU | International Telecommunications Union |
| MSF | call sign for the 60 kHz standard-frequency and time signal broadcast from the Rugby Radio Station |
| NIST | National Institute of Standards and Technology |
| NMS | National Measurement System |
| NMSD | National Measurement System Directorate |
| NPL | National Physical Laboratory |
| NTP | Network Time Protocol |
| SI | International System of Units |
| TAI | International Atomic Time |
| TWSTFT | Two-way Satellite Time and Frequency Transfer |
| UKAS | United Kingdom Accreditation Service |
| USNO | US Naval Observatory |
| UT | Universal Time |
| UTC | Coordinated Universal Time |
| LF | low frequency |

# ANNEX C: PROJECT DESCRIPTIONS

| **Project** | **Title** |
|---|---|
| T11 | The Maintenance and Development of UTC(NPL) |
| T12 | Algorithms and Analysis |
| T13 | Development of GNSS Time Transfer |
| T14 | Primary Frequency Standards |
| T15 | Secondary Representation of the SI Second |
| T16 | International Coordination and Representation |
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***Project T11 :***
**THE MAINTENANCE AND DEVELOPMENT OF UTC(NPL)**

## OBJECTIVES

To support the operation and development of the international civil time scale, Coordinated Universal Time (UTC), in partnership with the BIPM and the national time standards laboratories from other countries around the world.

To provide a reference time standard for the UK that is traceable to the international civil time scale, Coordinated Universal Time (UTC), with the uncertainty in the UTC-UTC(NPL) offsets published in the BIPM Circular T to be established with an uncertainty of ± 5 ns (1σ) or better.

## DELIVERABLES

- UTC(NPL), a continuously operating national time scale that is traceable to the international civil time scale, Coordinated Universal Time (UTC), with an uncertainty of ± 5 ns (1σ).

*Note that this deliverable incorporates the routine delivery of atomic clock, time transfer, and calibration data to the BIPM for the computation of Coordinated Universal Time (UTC). As such it directly supports the maintenance and development of the international time standard, UTC, while providing a top-level UK measurement facility.*

## BACKGROUND

Coordinated Universal Time (UTC) is a time scale that is the global basis for agreeing the date and time-of-day. It is also a mechanism for distributing the standard SI second around the world. UTC is computed by the Bureau International des Poids et Mesures (BIPM) each calendar month from measurements of atomic clocks and inter-laboratory time transfers between more than forty national time laboratories around the world. Each laboratory (*k*) maintains its local approximation to UTC known as UTC(*k*), and uses that reference to provide traceability to UTC. Here we provide some background information on the activities needed to support the maintenance and development of UTC.

Each laboratory maintains a number of atomic clocks, usually commercial hydrogen masers or caesium clocks. Most of the clocks are free running to provide unperturbed clock data for the BIPM computations. However, one of the laboratory's time references is adjusted (usually by applying frequency offsets) to stay in close agreement with UTC. The stability of UTC, and the ability of each UTC(k) to track UTC, is fundamentally limited by the noise processes in the underlying clocks. Active hydrogen masers have the best short and medium term stability of these commercial atomic clocks (phase fluctuations at the level of 100 picoseconds per day are a typical) but they suffer from a systematic drift in frequency that becomes significant over time periods of a few days. In contrast, the short-term instability of the best commercial caesium clocks is much worse (typically at the level of a few nanoseconds per day) but they do not suffer from frequency drift in the long-term. In simple terms, a caesium clock based ensemble will be better in the long-term (say for averaging times greater than 40 days) but an active hydrogen maser ensemble will perform better over shorter averaging times. The choice of any time scale is a balance between short-term and long-term requirements; the need for redundancy (to detect and overcome errors in individual clocks); and, of course, financial priorities. The choice of clocks for the NPL timescale is one that supports NPL's need for short-term and medium term stability in support of fundamental time metrology experiments and for steering UTC(NPL) to UTC. It also supports the BIPM's efforts in maintaining a global time standard that is stable over time periods of months and years.

The stability of the atomic clocks is matched by that of the time transfer links used to compare clocks in different laboratories. Two-Way Satellite Time and Frequency Transfer (TWSTFT) involves an exchange of time signals between two earth stations via a geostationary satellite. The fact that both stations broadcast and receive time signals simultaneously allows the travel-times of the signals to be eliminated almost entirely from the clock difference calculation. The impact of atmospheric propagation effects on the signal such as ionospheric and tropospheric delays are very substantially reduced and time-delays such as in the satellite

transponder may also cancel out. However, delays in the hardware of the earth stations do need to be taken into account and require careful calibration. Regular time transfer sessions within and between Europe and the US now routinely achieve a precision better than 1 nanosecond and the method is now used as the preferred technology for time transfer when computing International Atomic Time.
The main alternative to TWSTFT is common-view measurements of GPS (or other GNSS) signals. Differential GPS measurements are made between two or more GPS receivers at the same epoch. The measurements can include all available code (CA, P1 and P2) and phase (L1 and L2) parameters for geodetic receivers or a subset for less sophisticated receivers. Post processing of the data can then take place: either at a UTC(k) laboratory for simple BIPM format receivers or at an analysis centre equipped to handle geodetic GPS data if appropriate. It is important to note that the receiver’s internal clock used in the timing of the pseudo range measurements to the satellite must be related to the atomic clock under test, using either an internal or external counter timer. It is important that the 1PPS generation for a GPS timing receiver used for frequency and time transfer must be directly related to the internal clock of the receiver. Very few GPS receivers are designed this way. Simple GPS time transfer receivers are stable to a few nanoseconds per day (comparable to a caesium atomic clock) while Geodetic GPS time transfer receivers have demonstrated delay stabilities of 100 picoseconds per day.

The organisation of these many systems and laboratories needs coordination, both at the laboratory level and at an international level. The CCTF, ITU and EUROMET all contribute to the organisation of international time standards.

**RATIONALE**
The UTC time scale and the SI second are at the heart of the UK’s economic life and hence it is appropriate for the UK to play a leading role in the maintenance and development of this global infrastructure.
By providing a very stable medium term frequency reference that would not otherwise be available, the highly stable UTC(k) timescale will support much of the clock development work at NPL, including the caesium and rubidium fountain developments and the development of optical frequency standards.
The timescale would also be made available to UK clock manufacturers and colleagues working in satellite navigation. NPL will benefit by developing a UTC(k) timescale facility that will be a serious contender as a reference timescale for the European Galileo satellite navigation system.

**RISKS**
The biggest risk to the project comes from staff turnover, a problem experienced within the preceding time Programme (2000-2003). The work relies on continuous data logging, and equipment failures can have a major impact on progress. There is sufficient redundancy in NPL’s satellite time transfer capabilities, both in hardware and methods. However, failure of one of NPL’s active hydrogen masers would result in a major setback. The intention here is to buy a fourth to reduce the overall risk but, with lead times of up to two years, we will have to carry this risk for the majority of the programme.

**INTERRELATIONSHIPS**
This project provides the physical time reference for all the other technical work in the Programme.

Within Theme 1, it provides the interface between the primary frequency standard and International Atomic Time. It is the platform for new time scale algorithms and, in return, it benefits from the improvements delivered by those algorithms. UTC(NPL) is also the vehicle on which NPL may build its contribution to the Galileo system. It also provides the underpinning for the UK’s time and frequency dissemination.

**EXPLOITATION**
NPL is carrying out a number of Galileo timing related projects that support wider UK and European objectives. The UTC(NPL) facilities supported here provide the foundations for those Galileo activities.

### *Project T12 :*

## ALGORITHMS AND ANALYSIS

### OBJECTIVES

To extract the best possible performance from the UTC(NPL) time scale and time transfer links by developing and applying appropriate combining algorithms and analysis techniques.

### DELIVERABLES

- Development and implementation of a Kalman-filter based timescale algorithm facility for UTC(NPL) that is able to run real-time algorithms for operational and test purposes, by October 2004, and evaluation completed by October 2005.

- Development and demonstration of a proto-type TAI/GST steering algorithm based on NPL infrastructure, by October 2005 and evaluation completed by October 2006.

- Fundamental studies of time and frequency data analysis including the development of new techniques. These include work on: fractionally integrated noise structures; determining noise parameters; use of non-power law noise processes in time transfer and time scale algorithms; use of n-cornered hats in noise parameter determination; incorporating fractionally integrated noise structures and non-power law noise processes into a Kalman filter. The work will be presented during the course of the Programme in the form of at least five technical notes and at least two publications in referred journals.

### BACKGROUND

The NPL time scale infrastucture has developed to a stage where operational time scale algorithms are able to enhance the overall system performance (this was not the case at the start of the previous Programme in 2000) and where there are now both internal and external customers who require those performance enhancements. Internal NPL customers are found in the Time, Quantum and Length programmes, where they typically need stable and accurate frequency references when carrying out R&D on atomic frequency standards. The main external driver for improved performance is the Galileo satellite navigation system, which offers the opportunity to disseminate accurate time to a global audience. In both cases there is a need to combine clocks to achieve a more stable overall time scale (i.e. a time scale algorithm) and a need to predict UTC (and hence the time and frequency of UTC(NPL)) in advance of the monthly publication of the BIPM. Circular T. This project proposes to address both of these topics, supported by fundamental studies into the mathematical techniques that underpin these developments.

Over the past five years there has been collaborative work undertaken at NPL between staff in Time Metrology and in Mathematics and Scientific Computing, on examining the fundamentals of analysing timescale and time transfer measurements. There have been significant successes including the acceptance for publication in Metrologia of two papers describing NPL's techniques for resolving noise parameters [1] and analysing regular but unevenly spaced data [2]. The upgrading of both timescale and time transfer hardware during recent years has provided scope for further timescale analysis and algorithm development. NPL now has three active hydrogen masers and a caesium fountain clock becoming operational. The development of a timescale and clock steering algorithm makes much mores sense now than it did 10 years ago when UTC(NPL) depended only upon a single hydrogen maser. Similarly NPL now possesses an ensemble of time transfer hardware, including two TWSTFT earth stations, two geodetic quality GPS/GNSS receivers and at least three operational GPS common-view receivers.

NPL is developing Kalman filter based algorithms. These are a good fit with the noise parameter studies previously undertaken, as the noise parameters must be determined before the operation of the filter. This determination is likely to require the combination of well-established n-cornered hat techniques with NPL's methods of noise parameter determination. The algorithms will require the operation of a Kalman filter in the presence of fractionally integrated noise processes and non-power law noise processes. The optimal use of a Kalman filter under these conditions remains a challenge.

Finally, we consider the requirement to predict the offset between TAI and Galileo System Time. The success of GPS, and its underpinning role for other technologies (e.g. telecommunications, broadcasting, power distribution, etc.) has stimulated the European Commission and the European Space Agency to jointly develop a second generation satellite navigation system known as Galileo. As with GPS, Galileo has the potential to distribute standard time to a global audience if a suitable Galileo Time Interface (GTI) is established between UTC and the Galileo system. A GTI would enable Galileo System Time (GST) to be steered towards International Atomic Time (TAI) and would provides UTC parameters in the navigation message that allow users to access UTC.

**RISKS**

The biggest risk to the project comes the fact that the work depends on the skills of a few very specialised experts. Any unexpected staff turnover in this area could severely hamper progress.

NPL only has three active hydrogen masers that would form the basis of any time scale algorithm, along with measurements from NPL's caesium fountain clock. The failure of one of NPL's active hydrogen masers would result in a major setback. The intention here is to buy a fourth to reduce the overall risk but, with lead times of up to two years, we will have to carry this risk for the majority of the programme.

The analysis techniques used are often original, however NPL is able to reduce the risk of failure by having well established techniques as a fall back position

**INTERRELATIONSHIPS**

This project will provide the tools to make optimal use of the hardware being maintained and developed in the other core time projects.

**EXPLOITATION**

NPL should be able to generate a much more stable timescale following the implementation of the clock-combining algorithm. This should help NPL to achieve its aspiration of becoming a UTC(k) timing laboratory and also in providing a stable frequency reference for clock development work within NPL.

**REFERENCES**

Harris P M, Davis J A, Cox M G and Shemar S L, "Least-squares analysis of time series data and its application to two-way satellite time and frequency transfer measurements", *Metrologia* **40***(3), 2003, S342-S347.*

Davis J A, Harris P M, Shemar S L and Cox M G, "The characterisation of regular but unevenly spaced TWSTFT data using second difference statistics", *Metrologia* **40***(3), 2003, S312-S318.*

***Project T13 :***
**DEVELOPMENT OF GNSS TIME TRANSFER**

**OBJECTIVES**

To assess and prioritise the GNSS time transfer techniques that can be applied for time metrology

**DELIVERABLES**

- An assessment of GNSS time transfer methods (to include high-level options, current best-practice, fundamental limits, data transfer/processing issues, new signals and technology developments) with recommendations on further studies by February 2005.
- Experimental studies of new GNSS time transfer methods as defined by deliverable 1, to be completed by end September 2006.
- A cost-benefit analysis of the high-level GNSS time transfer options, with recommendations and implementation plans for options to be taken forward within the NMS Time Programme, to be completed by March 2006.

**BACKGROUND**

GPS common-view is one of the most important methods for comparing time standards around the world. In addition, GPS timing receivers are probably the dominant mechanism by which standard time and frequency is distributed to end-users. Given that many timing receiver products are being replaced by new technology, sometimes with a loss of timing functionality (e.g. the Motorola VPOncore), and that new signals are appearing or are being planned, it is essential to keep track of both scientific and technological developments.

Here we survey some of the activities in recent years:

Single-channel C/A-code GPS common-view measurements have been used for time transfer links within TAI since the mid-1980’s. The BIPM standardised the common-view data format (in order to standardise the data processing) in the early-1990’s. The BIPM format was extended for multi-channel C/A-code GPS and GLONASS in the late-1990’s. Ionosphere corrections are applied to long-baseline (i.e. inter-continental) links, currently based on IGS ionosphere maps.

Experiments with geodetic quality GPS receivers for precise timing began in the mid-1990’s and was pursued through a joint BIPM / IGS pilot project. The complexity (and hence the additional resources required) in routinely processing Geodetic GPS data has prevented BIPM from using this method operationally. Recent work at the BIPM has concentrated on the use of the P3 (code only) measurements for time transfer. There are groups, within the context of the International GPS Service, who provide data processing facilities for time scale products based on geodetic analysis techniques (see references below). However, long-term support for international time standards from these groups cannot be guaranteed.

Single or Multi-channel C/A-code GPS common-view receivers are used widely within TAI. The current data format (originally developed for single-channel receivers) is not optimum but remains unchanged because of the number of legacy receivers. Geodetic receivers are used in assessing TWSTFT links but have not gone into regular operational use. Software has been developed to convert Geodetic data (i.e. extended RINEX) into the BIPM format, so that some basic data from Geodetic time transfer can be applied within TAI. Clock noise dominates over the GNSS time transfer noise at averaging times above a few days so this is acceptable for many TAI computations. However, it does mean that the time laboratories are working with out-dated data processing methods, largely for historical reasons.

**RATIONALE**

Geodetic GNSS time transfer techniques clearly have great potential for supporting the production of UTC and for assessing primary frequency standards. Skills and software exist in the Geodesy community that can support time transfer developments but the time community needs to take greater ownership of the technology if it is to emerge from a research phase into operational use. The aim of this study is to explore the technical and financial issues behind developing a dedicated Geodetic time transfer capability within the time community.

**RISKS**

The project assumes support from the Geodetic community.

**INTERRELATIONSHIPS**

The project builds on the GNSS facilities of project T11 and is a promising candidate for knowledge transfer outputs in project T31.

**EXPLOITATION**

If successful, the project would support time transfer improvements for both UTC(NPL) and for best-practice advice in the Knowledge Transfer programme.

***Project T14 :***
**PRIMARY FREQUENCY STANDARDS**

## OBJECTIVES

To realise the SI second at the highest levels of accuracy and to relate those measurements to International Atomic Time (TAI).

## DELIVERABLES

- Realisations of the SI second with an uncertainty better than 3 parts in $10^{15}$ contributing to TAI in each year of the Programme, supported by research on laser-cooling and spin-exchange collisions with the aim of further improving the accuracy in successive realisations.

*Note that CCTF guidelines require that this work be supported by a peer-reviewed publication quantifying the uncertainty of the primary frequency standard.*

## BACKGROUND

The means by which the BIPM establish the accuracy of International Atomic Time (TAI) is from realisations of the second from primary frequency standards operated by a small number of NMIs. During the last decade those primary standards utilising a continuous caesium beam have been overtaken in accuracy by the caesium fountain. The fountain device uses lasers to cool and launch a cloud of caesium atoms vertically through a microwave cavity. The improved uncertainty arises from a combination of a longer measurement time and a simplified microwave interaction. SYRTE (formerly LPTF) in Paris have led the field in the accuracy of their fountain but very rarely contribute a measurement to TAI. PTB and NIST also operate fountains with similar accuracy but make more frequent contributions. A caesium fountain primary standard has been under development at NPL for a number of years. Currently, we have two fountains, at different stages of development. In the current Time Programme we have focussed on obtaining an internationally competitive uncertainty budget for one device and on improving the frequency stability. We are also developing a second fountain, which is to include a novel cooling scheme for the purpose of reducing the uncertainty due to spin-exchange collisions whilst delivering the same or improved frequency stability. We anticipate that this second fountain will offer the possibility of greater accuracy and stability than those currently operated by other NMIs.

## RATIONALE

The principal beneficiary of this work is the international time and frequency scale. Since virtually all precision measurement involve a frequency measurement, the resulting beneficiaries are very widespread and diverse. If we focus on the beneficiary for improvements to TAI and UTC(NPL) at the highest level, we should identify the geophysics and astronomy research communities, together with those enterprises seeking to exploit opportunities afforded by GNSS systems.

Research into future frequency standards at optical frequencies has reached the stage where it is important to measure the absolute frequency of atomic transitions at an accuracy obtainable only by having a local realisation of the second. NPL has an internationally competitive position that will be eroded if such traceability is not available.

## RISKS

There are scientific and technical challenges due to the innovative nature of the work, particularly that part exploiting the novel cooling techniques and the subtleties of the microwave interaction.

## INTERRELATIONSHIPS

The project depends on the UTC(NPL) time scale and its time transfer links (i.e. Project T11) to transfer its realisations of the SI second into TAI.

It also has strong links to the NMS Length and NMS Quantum Programmes were there are strong activities on optical frequency standards, optical and microwave oscillators, and on femto-second frequency combs to intercompare optical and microwave frequency standards.

## EXPLOITATION

The work will be exploited through NPL's contributions to International Atomic Time (TAI), through its contributions to the joint CCTF-CCL working group on secondary representations of the second (i.e. the group that is exploring the use of new atomic resonances for maintaining TAI), and through publication of research results in journals and at conferences.

***Project T15 :***
**SECONDARY REPRESENTATION OF THE SI SECOND**

## OBJECTIVES

To provide an ultra-high stability microwave frequency standard to underpin the uncertainty analysis of the primary standards of time and length.

## DELIVERABLES

- An ultra-high stability microwave frequency standard to underpin the uncertainty analysis of the primary standards of time and length. Specifically, a high-flux rubidium-87 fountain with a cryogenic sapphire-ring resonator with a target frequency stability of 5 parts in $10^{14}$ at one second averaging time and 5 parts in $10^{15}$ at 100 seconds averaging time**.**

## BACKGROUND

The SI second is defined in terms of the caesium-133 atom, with little prospect of this changing in the near term. However, the Consultative Committee for Time and Frequency (CCTF) has recently recognised the promise of improved frequency standards both at microwave and optical frequencies. A working group has been formed to consider candidates for alternative representations of the second. The medium-term prospect is one where NMIs operate a number of different types of "clock" contributing to international timekeeping as "secondary representations of the second". Some of these clocks may demonstrate higher stability than Cs devices. Some may also prove to be more accurate in representing the frequency of a transition in an unperturbed atom of the species on which they are based, promising greater long-term stability. One such candidate clock is a "high-flux" rubidium-87 fountain.

The dominant systematic uncertainty of caesium fountain primary standards is the spin-exchange shift due to collisions between the cold Cs atoms. In contrast, the cold-collisional shift for Rb-87 atoms is insignificant. This allows a rubidium-87 fountain to be run at much higher atomic fluxes, affording a lower limit on stability as set by quantum projection noise. We propose to utilise recent developments in Bose Einstein Condensate research to obtain a higher flux of rubidium than can be obtained from a single magneto-optical trap. Quantitatively, it is expected that the stability will again be limited by the atom flux but at one order of magnitude better than for the caesium standard.

Being a pulsed device, the fountain relies on a phase flywheel during the time between two interactions of the atom cloud with the microwave field. Current quartz-crystal-based microwave local oscillators limit the short-term stability at the high atom fluxes proposed. We plan to extend our cryogenic sapphire oscillator, developed for the caesium fountain, in the current Quantum Programme, to suppress this limit.

The Scientific Generics "Forward Look for the NMS Quantum Programme" (November 2002) has highlighted the importance of cold collisions in microwave frequency standards by suggesting that the formulation exercise include a survey of the outlook for frequency standards utilising microwave transitions in rubidium.

## RATIONALE

Three immediate beneficiaries of a high-stability (high-flux) Rb-87 reference are:

The national time scale, UTC(NPL) would benefit from improved understanding of the noise processes limiting NPL's H-maser ensemble. This can be achieved through comparisons with the Rb-87 reference which would have higher stability than a hydrogen maser at all averaging times.

Research into future frequency standards at optical frequencies. This work has reached the stage where it is important to measure the absolute frequency of atomic transitions at an accuracy obtainable only by having a local realisation of the second and by having a low noise transfer process from microwave to optical frequency. NPL has an internationally competitive position, which will be eroded if these are not available. A rigorous quantification and understanding of the noise processes that limit the ability of femto-second optical comb generators to transfer the SI second to optical frequencies will require state-of-the-art measurements of phase noise at microwave frequencies. In this context, a rubidium-87 fountain would act as an ultra-stable reference oscillator for phase-noise beat measurements.

The international atomic timescale: higher stability (lower collisional shift) caesium fountains, as primary frequency standards, would benefit from a stable, independent reference for calibrating systematic errors. Further, the rubidium fountain is a candidate for an alternative representation of the second. In the medium-term the device could be operated as a “clock” contributing to international timekeeping, with higher stability than caesium devices.

**RISKS**

This proposal has a degree of risk associated with the innovative aspects of the atomic and laser physics, and the low noise microwave synthesis

**INTERRELATIONSHIPS**

The project impacts the development of UTC(NPL), optical clock research, caesium primary standard research, and microwave to optical translation.

**EXPLOITATION**

The work will be exploited through NPL’s contributions to International Atomic Time (TAI), through its contributions to the joint CCTF-CCL working group on secondary representations of the second (i.e. the group that is exploring the use of new atomic resonances for maintaining TAI), and through publication of research results in journals and at conferences.

***Project T16 :***
**INTERNATIONAL COORDINATION AND REPRESENTATION**

**OBJECTIVES**
To represent UK interests on the international committees with primary responsibility for maintaining and disseminating civil time standards.

**DELIVERABLES**
This project will support UK representation at the following international committees with primary responsibility for maintaining and disseminating civil time standards:

- Consultative Committee for Time & Frequency (CCTF)
- International Telecommunications Union Radiocommunications Sector (ITU-R) Working Party 7A
- EUROMET Technical Committee for Time & Frequency

**BACKGROUND**
There are two international committees involved in coordinating civil time standards on a worldwide basis.

The Consultative Committee for Time & Frequency (formerly the Consultative Committee for the Definition of the second) advises the BIPM on time and frequency standards. This role is important because it is the BIPM who compute the global time standard, Coordinated Universal Time. In the past, the work of this committee has led to the redefinition of the SI second (1960, 1967) and to the recommendation that TAI and UTC be adopted for global time keeping (1971, 1975). Its activities in recent years have focused on primary frequency standards and time scales.

ITU-R Working Party 7A is concerned with the dissemination, reception and coordination of standard-frequency and time-signal services on a worldwide basis. ITU-R Working Party 7A is significant for time metrology for three main reasons: firstly, it defines the top-level procedures for maintaining the global time standard, Coordinated Universal Time (see ITU-R Recommendation TF.460); secondly, it recommends UTC as the standard time for radio broadcasts so that UTC is *de-facto* the time made available to end-users; and thirdly, it provides a mechanism for protecting the spectrum used for radio broadcasts of standard-frequency and time signals.

The EUROMET Technical Committee for Time & Frequency complements the activities of the CCTF at the European level. A significant aspect of its work in recent years has been support for the Mutual Recognition Arrangement (MRA). The MRA is designed to develop a framework to give users reliable quantitative information on the comparability of national metrology services and to provide the technical basis for wider agreements negotiated for international trade, commerce and regulatory affairs.

There are many other international committees that support time standards for particular user groups (e.g. International Astronomical Union (IAU) Commission 31 on Time) of for particular technologies (e.g. Internet Engineering Task Force Working Group on Secure Network Time Protocol). The aim of this project is not to engage with every such committee. Instead, it seeks to support the coordination of International Atomic Time (TAI) and Coordinated Universal Time (UTC).

**RATIONALE**
Time-keeping is an international activity and it is essential that the UK national effort is properly coordinated with that of our peers in other countries.

**RISKS**
The main risk is in terms of resource commitment where any new initiatives emerging from these committees might require work plans to be revised to reflect new priorities.

**INTERRELATIONSHIPS**

The CCTF activities underpin the work in Theme 1 directed towards the maintenance and development of UTC and primary frequency standards. The ITU-R Working Party 7A activities support the dissemination of standard time, and hence projects in Theme 2. EUROMET is important in terms of initiatives to coordinate metrology across Europe and it has a central role in terms of the provision and recognition of national measurement standards on a global basis. As such, it supports the time dissemination activities in Theme 2 and engages with wider NMS activities coordinated by the NMS International Programme.

**EXPLOITATION**

The coordination activities here feedback into technical projects and will be used to inform Knowledge Transfer activities as appropriate.

***Project T21:***
**MSF STANDARD-FREQUENCY AND TIME BROADCAST**

## OBJECTIVES

To support the operation and future development of the MSF standard-frequency and time signal.

## DELIVERABLES

- The MSF 60 kHz standard time and frequency signal, delivering time with an accuracy of ± 2 ms and frequency with an accuracy of ± 3 parts in $10^{12}$ over one day.

- An MSF Information Service, including:
  - Background information and status reports for MSF users on the Internet, also available in printed form on request;
  - An annual mail shot (by post and e-mail) giving dates for future scheduled outages, a report on the MSF signal performance in the past year, and news of any changes to the service.
  - A telephone information service (unmanned) giving brief details of the service and dates for the scheduled outages each year.

***The Future of the MSF Service***

*In addition to the specific deliverables identified above, there will be a set of ongoing activities related to the long-term future of the MSF service. The current broadcast contract with BT runs until 31 March 2007 after which new arrangements will need to be in place if the MSF service is to continue. The NMS is committed to establishing a firm decision on the long-term future of the MSF service by March 2004. NPL will support that decision-making process with information and ideas. NPL will also support the actions that follow the decision. Specific actions will be agreed with the NMS Directorate at DTI on an ongoing basis to reflect developments throughout the Programme. It is understood that the MSF Information Service will provide news and information on these developments to end-users throughout the course of the programme.*

## BACKGROUND

The MSF time and frequency signal has been broadcast from the Rugby Radio Station for over fifty years, and since 1967 has been under the control of the NPL. In its current form, the 60 kHz carrier-frequency is controlled by atomic frequency standards to provide a traceable reference frequency, and the signal carries a binary-coded decimal “slow” code that provides time-of-day and date information. The signal can be received over the whole of the UK, and is extensively used by both businesses and the general public. The MSF service is subject to a long-term contract with BT and will continue to be broadcast from the Rugby Radio Station over the lifetime of the next Programme. In addition to maintaining the MSF broadcasts, the project will provide supporting information for users of the service. This framework is the basis for the first two top-level deliverables identified above.

The final set of comments in the deliverables section reflects the fact that the end of the current broadcast contract is approaching, in 2007. A decision on the long-term future of MSF is anticipated in March 2007, after which a new broadcast contract will need to be negotiated or preparations for the termination of the service will need to be put in place. Looking to the experiences in other countries, we note that the LF time services in Japan (JJY) and the US (WWVB) have undergone substantial upgrades in the past 5 years. The ability of LF signals to penetrate buildings, the fact that they broadcast the local time of the host country (i.e. changes for summer time are catered for), and the fact that they provide a relatively inexpensive back-up to other time signals such as GPS, all seem to have been factors in those decisions.

**RATIONALE**

The MSF service has a very wide user base in commercial, industrial and domestic applications that needs to be supported throughout the life of the next Programme. In addition, the end of the current MSF broadcast contract in 2007 makes it imperative for the next Programme to resolve the technical and contractual issues for the long-term provision of the MSF Service.

**RISKS**

The project is a continuation of existing MSF services and so the level of risk here is relatively low.

However, the need to decide on the long-term future of the MSF service and to act on that decision presents unique challenges that need to be managed carefully.

**INTERRELATIONSHIPS**

The project is dependent on the facilities provided in Projects T11 (i.e. for a source of UTC) and Project T31 to distribute information on these services.

The project shares monitoring facilities with Project T22 for the broadcast of the MSF 60 kHz standard-frequency and time signal.

Support for the 60 kHz frequency allocation, through attendance at UK Study Group 7 and ITU-R Working Party 7A meetings is addressed in Project T16.

**EXPLOITATION**

The MSF service is already very widely used within the UK and appears to have an expanding user-base, despite the availability of GPS that can provide substantially greater accuracy. This project provides a mechanism for distributing standard time to the user-community. It also helps to promote the Programme by demonstrating ready public access to the UTC(NPL) time scale.

***Project T22 :***
**MONITORING OFF-AIR TIME AND FREQUENCY SIGNALS**

## OBJECTIVES

To validate the time and frequency radio signals most commonly used in the UK, and where appropriate to provide regular information that allows a user to demonstrate traceability from one of the signals to the UK national time scale UTC(NPL).

## DELIVERABLES

The following deliverables will be provided for the GPS, MSF 60 kHz and Droitwich 198 kHz standard-frequency and time signals:

- Monthly bulletins reporting the accuracy and integrity of those signals to be published in print and on the Internet.

- User Guides describing how the Bulletins can be used with each standard-frequency and time signal to provide the user with accurate and reliable time and frequency measurement standards.

- An e-mail broadcast service to report anomalies and items of general news related to the standard-frequency and time signal.

## BACKGROUND

Many applications are able to use standard-frequency and time signals, and accept the specifications associated with those signals. However, some applications require greater security and will look for independent validation that the signal is indeed operating within its specified performance limits. For example, some 90 UK calibration laboratories receive NPL Bulletins for GPS, MSF and Droitwich, the majority using them to confirm whether the signals were behaving normally or not. Another set of users will need better accuracy than the broadcast signal is able to deliver. In that situation, the signal is calibrated against the national time standard so that other standards can apply corrections to their own measurements. In this situation, the received signal is used as a vehicle for transferring the national time standard to remote laboratories.

The carrier frequencies of the MSF 60 kHz and Droitwich 198 kHz radio signals, and timing signals from GPS satellites, are monitored at the NPL. The results are published as daily values of the phase offset in monthly bulletins. The project will carry out routine monitoring of MSF, Droitwich and GPS, and publish data on the accuracy and integrity of those signals. The prime purpose of this activity is to support traceable time and frequency measurements here in the UK. However, some signals have wider application than just metrology. Both MSF and GPS broadcast Coordinated Universal Time (UTC), and hence are used widely in many communications applications. MSF and GPS integrity data is likely to be of interest to this wider user community.

## RATIONALE

The monthly bulletins are distributed to around 115 customers by post and a further 15 by e-mail, and provide the means for users of those signals to obtain traceability to the UK national time scale UTC(NPL).

## RISKS

The project is a continuation of existing services and so the level of risk is low.

## INTERRELATIONSHIPS

The project is dependent on the facilities provided in Projects T11 (i.e. for a source of UTC) and Project T31 to distribute information on these services.

The project shares monitoring facilities with Project T21 for the broadcast of the MSF 60 kHz standard-frequency and time signal.

## EXPLOITATION

This project provides a mechanism for distributing standard time to a key user community. It also helps to promote the Programme by demonstrating ready public access to the UTC(NPL) time scale.

***Project T23 :***
**COMPUTER TIME SERVICES**

## OBJECTIVES

To provide access to the UK national time standard via telephone and the Internet.

## DELIVERABLES

- A continuously operating telephone time service providing time with an accuracy of ± 50 ms or better.
- A continuously operating Internet time service providing time with an accuracy of ± 1 s or better.
- User Guides for the telephone and Internet time services.
- Annual reports on technical and market developments in time-stamping for secure electronic document exchange.

## BACKGROUND

Most national time laboratories provide public access to their time scales over telephone and Internet links. The aim here is for moderate time accuracy to be delivered to a large number of users. The time-base in most computers is poor (a drift of tens of seconds each day is not uncommon) and so it makes sense to provide them with access to standard time over the communication channels they already use (i.e. modem/telephone line and Internet).

NPL has been operating a premium rate telephone time service since 1994. Software for the service can be downloaded from the NPL web-site (or posted on disk if requested), and the service typically receives 500 calls to each week. Calls are all routed to just one premium rate telephone number, but two back-up lines with separate time code equipment can be switched in if faults occur on the main service. The service is not easily scalable in its current form, and the access limit is set by call congestion rates. In principle, the service could be reconfigured to accept more calls (e.g. by introducing automatic routing of calls between multiple time code units). However, the current level of demand for the telephone time have been static over the last three years and Internet time distribution channels are much more pervasive than when the service was started in the early 1990's. On that basis, we propose here to continue the current level of service.

The Network Time Protocol (NTP) has become the dominant mechanism for distributing time over the Internet. NTP incorporates a number of features to improve the accuracy and reliability of Internet time distribution. Firstly, it measures the round-trip delay in sending data packets from one server to another and corrects for that delay when transferring the time (i.e. it assumes that time delay in sending the signal from server to another is half the round-trip delay. Internet transmission paths are not always symmetric and so systematic errors can occur at this level). Secondly, it establishes a traceability hierarchy to assist the diffusion of standard time across the Internet. A Stratum 1 server is synchronised directly to a UTC source (i.e. a radio time signal such as GPS or MSF, or directly to a UTC(k) laboratory). A Stratum 2 server takes its time from one or more Stratum 1 servers. The Stratum 2 servers will then re-distribute time to a number of local clients (at Stratum 3 or below). The informal rules that are followed require users to access time from a Stratum 2 server to reduce congestion at the Stratum 1 level. Thirdly, NTP allows a server to take time from several servers, and then filters that information to remove erroneous time inputs. The protocol operates both on publicly accessible servers (there are approximately 200 public Stratum 1 servers) and on private networks. In the latter case, many organisations prefer to restrict public access to their network (as is required for NTP exchanges) and hence install their own NTP servers within their firewall. Most time and frequency suppliers have NTP products as part of their portfolio of products.

There is great interest in extending NTP capabilities to incorporate greater security. Typically, this involves the application of public key cryptography techniques to embed a time stamp in an electronic document. The purpose is to create a time stamp that cannot be tampered with, and one whose accuracy and provenance can be proved. One company has coined the phrase “Trusted Time” to convey the added benefits of this type of time service. There is great interest both from NMIs and from some timing companies in providing such services, although it is not clear what the uptake will be in the market place.

**RATIONALE**

Any customer in the UK can access the Telephone Time Service from their PC by running software that makes a premium-rate telephone call to connect to a server at the NPL, downloads the time code, and synchronises the PC clock to the correct time. The NTP service provides a means to access time traceable to UTC(NPL) via the Internet, using what is perhaps the most widely used method of obtaining time to within 1 second uncertainty.

**RISKS**

The computer time services operated by NPL depend on the IT and telecommunications infrastructure at NPL.

**INTERRELATIONSHIPS**

The project is dependent on the facilities provided in Projects T11 (i.e. for a source of UTC) and Project T31 to distribute information on the computer time services.

The monitoring activity into time-stamping for secure electronic document exchange is designed to alert the Programme as to progress in this area. There is a “deep study” in Project T31 (Knowledge Transfer) that could be activated if significant developments are detected to which the NMS would need to respond.

**EXPLOITATION**

This project provides a mechanism for distributing standard time to a key user community. It also helps to promote the Programme by demonstrating ready public access to the UTC(NPL) time scale.

**REFERENCES**

Authenticating Time and Frequency Signals, J Levine, Proc. EFTF/ IEEE FCS 1999, 304-308
Internet Timekeeping Around The Globe, D Mills et al., Proc. PTTI 1997, 365-371

***Project T31:***
**KNOWLEDGE TRANSFER**

**OBJECTIVES**

To promote the NMS Time Programme and its key outputs to UK industry.

To provide general information and advice on Time metrology matters for users in the UK.

To support dialogue between the NMS Programme and UK timing specialists, and to work with those specialists to promote best practice among the wider user community in the UK.

To respond to new issues and concerns for the timing community as they arise during the course of the Programme.

To ensure best practice is developed and used in all aspects of knowledge exploitation within the Programme.

**DELIVERABLES**

- An Awareness Strategy and Campaign for the NMS Time Programme
  The objective of making the programme available and accessible to UK industry will be supported by a formal awareness strategy, to be developed in the first six months of the Programme. The subsequent awareness campaign will expose and promote the programme to a wider audience, for example, by exploiting the knowledge transfer potential of partnerships with like-minded programmes and professional bodies such as the Pinpoint Faraday Partnership, the Institution of Electrical Engineers (IEE), and the Institute of Physics (IoP).

- An NMS Time Metrology Information and Advice Service
  An advice service accepting enquiries by telephone, letter, E-mail or fax to answer queries received each year in relation to time and frequency issues in the UK The Information and Advice service is supported by web pages with answers to frequently asked questions, details on research carried out as part of the programme and links to relevant external projects.

- NMS Time & Frequency User Club
  To provide an independent forum for communication and information exchange on timing issues in the UK. To facilitate dialogue between the NMS Time Programme and the community of timing specialists in the UK. To support those timing specialists in promoting best practice amongst their own user communities. The Club will operate five meetings and circulate five newsletters over the course of the Programme.

- Impact measures
  To measure and record the impact of the Programme in a structured manner and use this information to ensure effective knowledge transfer across the whole programme
  Details of impact assessment to be included in annual reporting to DTI

**BACKGROUND**

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 Time 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 Time 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. The other activity, the NMS Time & Frequency User Club, has been operated by Quartzlock Ltd during the 2000-2003 Programme.

This project proposal incorporates three new features to Knowledge Transfer in the NMS Time Programme. One is a top-level awareness strategy and plan, to promote the benefits of the programme more actively. Previous activities have either been channelled through other NMS Programmes (e.g. ‘millennium’ activities undertaken as part of the NMS General Activities Programme) or have occurred in response to external events (e.g. general press enquiries on time measurements issues). A second new activity is the Impact Measures, to capture and review the success (or otherwise) of specific knowledge transfer activities across the Programme. The third is the introduction of new studies as part of the knowledge transfer project to provide resource for new issues and directions to be assessed during the course of the Programme. In previous NMS Programmes, such activities have often taken place as part of the Programme Formulation exercise, restricting the time frame in which they can be activated to a window of just a few months at the start of the final year of the Programme.

## RATIONALE

The Government’s 2000 White Paper on science and innovation noted, “*knowledge must flow out of the science base into products and services. All industries will benefit from this knowledge flow, from basic manufacturing and food processing, to the new science-based industries of the future*”. In addition to benefiting from this knowledge, easy access to publicly funded research will enable companies to develop competitive advantage.

The work in this proposal aims to address this issue to ensure that information and knowledge generated in the NMS Time programme is transferred to industry in an efficient and effective manner. This work will promote the entire programme as well as assisting with effective KT of the individual projects. This work will also ensure effective client relationships and knowledge management for the programme.

## RISKS

The largest risk is the possibility of damaging the DTI’s or NPL’s reputation through disorganised or poorly planned activities. As knowledge transfer activities are the primary interface between UK national measurement laboratories and DTI, and UK industry they must be competently performed. By taking steps to reduce both the impact and the probability of defined risks, the potential for harm is much reduced.

A secondary risk to be managed is the impact of enquiries on the technical work of the Programme. At present, NPL adopts a layered approach to enquiries where the NPL general enquiry line field most enquiries, passing on any non-standard or technical questions to the scientists and engineers working on NMS Time Programme projects. This buffer allows callers to gain access to the information they need, while only using specialist resources when essential.

## INTERRELATIONSHIPS

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 Time Programme is available for dissemination to as wide an audience as possible. If people have access to information about the NMS Time programme, it can increase the amount of potential collaboration on other projects.

## EXPLOITATION

The effective exploitation of the programme work can be enhanced through liaison with similar programmes as well as relevant bodies.

***Project T41:***
**PROGRAMME MANAGEMENT**

## OBJECTIVES

To manage the delivery of the whole programme and to ensure that objectives are met within time and budget.

To inform the NMSD of progress in delivering the agreed Programme and of any issues affecting the delivery or future direction of the Programme.

## DELIVERABLES

- Monthly and Annual progress reports to NMSD, highlighting achievements and problems and recommending any necessary programme modifications.

## BACKGROUND

This project will provide the overall co-ordination functions for the NMS Time Programme 2003-2006. Progress reports will be provided to NMSD on both a monthly and an annual basis, in addition to any general liaison activities for the NMSD. The Programme coordination activities will include the promotion of the objectives of the programme, monitoring the progress of all contractors on behalf of NMSD, liaison with NMSD on all technical and financial matters, and proposals to NMSD for programme modifications resulting from changing circumstances. Project managers are required to incorporate the necessary financial, operational, and quality management tasks within their projects and to report to the overall Programme Manager at monthly intervals or as necessary to facilitate provision of the above reports.

***Project T42:***
**FUTURE PROGRAMME DEVELOPMENT**

## OBJECTIVES

To assist the DTI in the identification and procurement of the most effective programme of work for the available budget, consistent with the agreed objectives of the NMS Programme.

## DELIVERABLES

- The formal procedures to develop the NMS Time Programme after September 2006 need to be confirmed. However, we assume a similar procedure to that outlined in the 'Background' description below with deliverables to match.

## BACKGROUND

NMS technical programmes typically run for three-year periods, and the process of preparing for the subsequent programmes begin approximately 18 months in advance. The current process sees a strategic assessment (the Orientation Phase), followed by detailed consultations with users and technical experts (the Formulation Phase). A specific programme of work is then proposed, made publicly available and comments invited (Public Consultation). The proposals are refined in the light of comments received, and then prioritised for the DTI by an industrial and academic advisory group. The agreed programme is then developed by the DTI into a set of single-tender contracts and ITTs as appropriate. We anticipate a similar process will take place to prepare for the NMS Time Programme 2006-2009.