

DTI Scouting Mission to Japan on Trapped Ions for Measurement and Enterprise (TIME) 26th – 30th November 2001

by

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EXECUTIVE SUMMARY

This report describes the findings of the DTI sponsored scouting mission to Japan “Trapped Ions for Measurement and Enterprise” (TIME). It focuses particularly on new optical frequency standards (for which trapped ions are strong candidates) and measurement of optical frequency standards using femtosecond comb laser systems. There has been a “sea change” in optical frequency metrology using these measurement systems, and ensuing technical developments are moving quickly, with potential implications for telecommunications and photonics, navigation and ultimately for time measurement. The mission examined what the UK and Japan have in common in this field and the scope for future collaborations. It included visits to two national laboratories, the National Metrology Institute of Japan (NMIJ) and the Communications Research Laboratory (CRL), two companies, Anritsu and NTT, and discussions with staff at the University of Electro-communications and Kyoto University.

At the National Physical Laboratory (NPL) in the UK and elsewhere there have recently been developments of femtosecond comb laser systems, which have been used to measure the absolute frequencies of several optical frequency standards including several very stable ion-trap based standards. In Japan these measurement systems at the National Metrology Institute of Japan (NMIJ) have been used to measure the optical frequencies of iodine stabilised lasers, but trapped-ion based optical standards still need development.

More detailed observations and conclusions include:

- The measurement opportunities offered by femtosecond laser comb technology were widely appreciated by scientists in Japan.
- Many of the laboratories we visited were very well equipped, in some cases better than those in the UK. For example NMIJ already had 5 femtosecond comb systems.
- A feasibility study on optical frequency standards and clocks was being started at CRL Koganei; future work would be likely to involve collaboration with the ion trapping researchers at the Kansai branch. The long-term direction of this work might well be towards optical clocks, however this concept is still at the planning stage.
- Staffing levels at some laboratories seemed low.
- Ministerial structures in Japan may have blocked formal links and collaborations within Japan in the past, but there were several examples of good technical links. Recent reorganisations may have helped address this issue.

There are many Japanese government initiatives to encourage collaboration with other countries, for example JST’s ICORP projects and NEDO International Development program projects which must involve foreign collaborators. One problem with trying to join these programmes is that on the UK side there is relatively little direct support for international research collaborations. The British Embassy in Tokyo has an active team headed by Dr Mike Norton (Science and Technology Counsellor) to help facilitate communications and contacts. The UK government might consider introducing schemes to fund joint projects of significant size. Interest in possible collaboration or partnership with the UK in the area of optical frequency measurement and standards was expressed by a number of Japanese researchers, for example at NMIJ and CRL.

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1. INTRODUCTION

Recent advances in the measurement of optical frequencies have led to a revolution in the domain of frequency metrology. In particular, the development of octave-spanning femtosecond combs means one can now directly link the frequency of an optical standard to that of the primary time standard, namely the caesium clock at 9.2 GHz. This advance is expected to have important ramifications for frequency and time metrology, a possible future consequence being a new definition of the second based on an optical transition in an atom or ion. Details are given by Diddams, Udem et al. 2001 and there is a review by Cundiff et al. 2001. Although the two major contributions in this field have come from Germany (Holzwarth et al. 2000) and the United States (Hall & Ye 2001), research is progressing rapidly in many places, among them Japan. The purpose of the DTI mission to Japan was to investigate the state of optical frequency metrology around the Tokyo area where many of the top Japanese laboratories are located.

Since many of the best optical frequency standards use cold trapped ions, the mission was entitled “Trapped Ions for Measurement and Enterprise” (TIME), though the scope of the investigation was somewhat larger. Its aims were to note any areas in time and frequency metrology where Japan has significant research or industrial development in order to learn from them and anticipate new trends. In addition, discussions were undertaken to study the possibility of collaborations at a research level. We were unable to investigate X-ray standards.

The dates of the mission were chosen to coincide with two days of seminars organised by the Japan Science and Technology Corporation (JST) – see Photo 1 - to celebrate the successful completion of a 5-year ICORP (Ohtani 2001) on the subject of “Cold Trapped Ions” involving Oxford University, the National Physical Laboratory (NPL) at Teddington, UK and the Electro-Communications University (ECU) at Chofu, Japan – see the NPL Press Release (see Appendix). The seminars provided the opportunity for a first contact between some mission members and staff at several of the institutions visited.

The 4-person team, led by Dr Hugh Klein (NPL) brought together expertise from atomic physics and time and frequency metrology.

Visits were chosen to gain a broad view of Japanese research, and included a university (UEC at Chofu), government-supported research institutes (AIST /NMIJ and FESTA, both at Tsukuba and CRL, Koganei) as well as two major industrial laboratories (Anritsu at Atsugi and NTT at Yokosuka). Given the limited time available, visits were confined to the Tokyo area. A special discussion was arranged with Dr Sugiyama from Kyoto University whose laboratory could not be visited. Some aspects of these visits and discussions are summarised in the Key Questions Table (Table 2) in the visits section, which follows.

The body of this report is in three parts: 2. Summary of visit details and outline of questions to organisations, 3. Detailed visit reports by organisation with tables of technical topics, 4. General observations and scope for collaboration. A conclusions section is then followed by acknowledgements, references, acronyms and abbreviations and an appendix.



Photo 1: Japanese Science and Technology (JST) hosted meeting with mission members. Back row from left: Mr Takahru Atago, Prof Shunsuke Ohtani, Mr Jiro Shibata and Mr Tsutomu Ueki. Front row from left: Dr Mark Plimmer, Dr David Knight, Professor Joshua Silver and Dr Hugh Klein.

2. SUMMARY OF VISIT DETAILS AND OUTLINE OF QUESTIONS TO ORGANISATIONS

2.1 Timetable

A brief timetable of the mission is presented below. Some items in Table 1 relate primarily to the ICORP, such as the JST meeting, the seminar and the symposium. The main items of interest to the TIME Mission are scientific visits to or discussions with 7 organisations. Of these two were universities (Chofu and Kyoto), two (NMIJ and CRL) were national metrology laboratories, two (Anritsu and NTT) were industrial companies and one (FESTA) was a joint research enterprise between government and industry. A typical visit lasted two to three hours.

Table 1: Timetable

Date	Visit or activity
26/11/01	Meeting with Dr Sugiyama, University of Kyoto, at Tokyo
	Institute for Laser Science, University of Electro-Communications, Chofu
	Meeting with Jiro Shibata, Executive Director, Japan Science and Technology Corporation
27/11/01	UK-JST Seminar on Cold Trapped Ions, British Embassy, Tokyo
	Anritsu Corporation, Atsugi Laboratory
28/11/01	JST-UK Symposium on New Trends in Atomic Physics, Museum of Emerging Science and Innovation, Odaiba
29/11/01	AIST-NMIJ and FESTA at Tsukuba
30/11/01	Communications Research Laboratory at Koganei
	NTT Laboratory at Yokosuka

2.2 Responses to the Key Questions

We carried with us the “Key Questions” shown in table 2. These questions ask about the field of optical frequency standards and applications of femtosecond-laser frequency combs, which have recently allowed direct measurement of optical frequencies from the microwave region. This changes the whole scenario for future time and frequency standards, since the new cold-atom or trapped-ion standards have a higher resolution than typical microwave standards – see Knight 2001. The Key Questions ask further about applications, future work or instruments that may use the new technology. Brief responses are given in Table 2 for the 7 organisations visited. Entries were recorded during visits and provide a structure for what follows in the report.

Table 2: Summary of the Key Questions and Responses

Key Question	Dr Sugiyama Kyoto & NMIJ	U. Electr. Comm. Chofu + JST	Anritsu (Atsugi)	NMIJ/AIST Tsukuba (length)	FESTA Tsukuba	CRL Koganei	NTT Yokosuka
What optical f & X-ray work do you do?	Yb ⁺ at 411nm	1500nm, C ₂ H ₂ , Rb 778 TP, BEC, atom interferometry	1500nm	532nm/1 ₂ , 1500nm C ₂ H ₂	1500nm	optical f measurement	1500nm [grid] generation +TDM
Do you do or plan f-s comb work?	Y. NMIJ also Kyoto	N – suggested Dr Sugiyama, Kyoto	N	Y. Have 5, incl. 2 fibre 1500nm	Y	Y. Next year	Y
Are you developing opt. f/λ standards? If Y, what type?	Cs is at NMIJ	1500nm C ₂ H ₂	Existing grating? spectrum analyser to 1500nm	Y. f & λ, [e.g. Yb ⁺ at 411nm]	N	Ion, at Kansai with Osaka U.	Y. ITU channels at 1500nm + 10 MHz to network
Do you plan to build “optical clocks”? If so, when?	longer term	(N)	Niche markets. OC too far off.	Have Cs ftn & H maser [so could]	N	Feasibility study. in progress.	Submm from opt. for RA ~2005/6
What strategic plans ... for optical clock development?				none	n/a		
What industrial applications for optical clocks do you foresee?		Factory calibrator for 1500nm		(gauge block cal. opt. comm. 10 ⁻⁸)	n/a	1500nm ITU grid at 12.5GHz Δf [also TAI, UTC] Few years	Submm? multi-channel gener.n opt. 10MHz std.
Over what time-scales do you see these needs arising?		NTT: needed now 1. 10 ⁻⁷ not met	Few years [hard to be sure]				
What plans do you have to address these?		Prototype but no manufacturer yet					
Have you analysed the size & evolution of the market?		N					
Where do you expect to see the strongest competitors?						maintain meas.t at parts in 10 ¹⁰ (VLBI earthquake market discussed) NIST pushing optical i/p to TAI	Distr. 10 MHz over opt. network
Do you see any uneconomic niche markets?			Agilent, USA Oscilloquartz, Eu *				
Are you interested in partnerships with UK companies & laboratories?		Y(JST) as ICORP	[perhaps if for a portable product]	[existing BIPM collaboration]	~9 Japan partners + 1 USA	Y, if a common interest	It res. with Nat. Obs. & USA, Eur for submm obs.y
Any other comments concerning the future of optical time & frequency standards?	University professors can now head their own companies	University professors can now head their own companies	Drullinger at NIST said main application of f-s might be FCs	improvements of OC portability suggested: 1. diode pumped f-s; 2 active vibration isolation	n/a	space applications discussed	Proc Jpn conf on Optical f meas.t given c2001, 16pp, Japanese

Notes: BEC: Bose-Einstein Condensation; Eu: Europe; FC: fundamental constant; ITU: International Telecommunications Union, Geneva; OC: optical clock; RA: radio astronomy; TDM: time division multiplexing; VLBI: very long baseline interferometry ; *: all these markets are “niche”

3. DETAILED VISIT REPORTS BY ORGANISATION

3.1 Dr Sugiyama, University of Kyoto (held in Tokyo)

Dr Sugiyama had recently moved from NMIJ, Tsukuba, and is transferring his work on ion traps and optical frequency measurement (Sugiyama et al. 2001) to the university. He will set up a comb system in Kyoto to provide an “optical clock” in the university. He has a Yb⁺ ion trap 5mm diameter (5 x larger than at NPL), interrogated on the 411 nm line, and plans to build a smaller trap. He has plans to build a Titanium-sapphire (Ti-sa) femtosecond laser with a prism pair and pulse repetition frequency (prf) of 100 MHz. Prof. Kitano is head of Quantum Optics Group at Kyoto and is interested in Bose-Einstein Condensation (BEC): they are doing laser cooling of Rb atoms. There are 3 students.

At Kyoto they plan to use the femtosecond comb to measure optical frequencies. They will use a rubidium microwave frequency standard referred to GPS for reference. For part-in-10¹⁵ measurement they would need to go to Tsukuba, where there is a national caesium standard. The 411 nm diode-laser system is narrowed by locking to a high-finesse cavity, the latter having no vibration protection system; the laser has a 5 kHz linewidth after pre-stabilisation to an invar cavity. They need to build up the cooling dye-laser system. Their present work is funded by the Ministry of Education. Dr Sugiyama has been working part-time at NMIJ/AIST during weekends over the last 6 months on the systems he built there.

We asked about commercial interest in femtosecond combs in Japan. Dr M Nakazawa (now a professor at Tohoku University) was previously at NTT, and now collaborates with NTT on femtosecond fibre lasers. In Japan, Mitsubishi Cable is making “holey” fibre (used to broaden the frequency comb of Ti-sa femtosecond lasers). We noted a report, that an octave comb had been produced without needing an optical fibre (Ell et al. 2001).

Dr Sugiyama would consider possible future collaboration, with NPL for example. It may be helpful in this connection that Dr Mike Norton at the British Embassy knows Prof. Nagao, head of Kyoto University.

3.2 Institute of Laser Science (ILS), University of Electro-Communication, Chofu

An important area of Dr Ken-ichi Nakagawa's work is wavelength standards for 1550nm using ¹³C₂H₂ acetylene. This was started 7 years ago and is now drawing to a close. They have developed stabilised lasers, in collaboration with Dr Onae at NMIJ (formerly NRLM) which lock to saturated-absorption features having linewidth typically 1 MHz. Since the transition is an overtone one with weak absorption, the gas is placed inside a Fabry-Perot resonator, which has the effect of multiplying both the laser intensity and the path through the gas. His system is a prototype bench calibration laser suitable for factories making optical communication equipment, having an accuracy of about 1 part in 10¹⁰, and a stability of about 2 parts in 10¹³ at 100s. A similar system exists at NMIJ-see below. Such a standard has become necessary because the commercial grating-based optical spectrum analysers are limited at the part in 10⁶ to part in 10⁷ level. The BIPM has adopted the frequency of one of its reference lines for the “Mise en pratique” for the metre. The absolute frequency was measured by using the known 778nm 2-photon Rb stabilised laser to measure the 2nd-harmonic frequency of the acetylene line.

Prof. Shimizu's impressive laboratory on laser cooling of neutral atoms had 8 or more well-equipped benches and large vacuum systems devoted to fundamental studies using laser manipulation of atoms. Li is the lightest alkali and they were the first group to trap it 10 years ago. They are also working on metastable Ne, studying quantum statistical properties. There is a student recruitment problem and the post-docs these days all want to go to JILA or MIT in the USA, or to Paris!

At ILS they are doing precise measurements in atom optics and BEC using ^{87}Rb , and are also doing measurements on the gravitational constants, g as Chu has done, and afterwards they plan to measure G following a recent Kasevich experiment at Yale. At present their sensitivity is not high. There is also Professor Ohtani's EBIT group (Ohtani 2001) with its work on highly-charged ions relevant to future X-ray standards.

3.3 Anritsu Corporation Atsugi Laboratory

We visited the laboratory of Dr Takahei, to see their new caesium laser-pumped gas-cell frequency standard at 9.2 GHz (Ohuchi, Y et al. 2000), and afterwards to discuss with a group of colleagues having microwave, optical and technology development experience the prospects for the recent "optical clock" developments. See Photo 2.



Photo 2: Anritsu staff and Mission members at Atsugi. From left: Dr Takanori Saitoh, Mr Yoji Sonobe, Dr Masaharu Uchino, Mr Yuuji Ōuchi, Dr Kenichiro Takahei, Dr David Knight, Dr Mark Plimmer, Professor Joshua Silver and Dr Hugh Klein.

The Cs cell standard is an important industrial departure in the world of microwave caesium standards, and is thought suitable to back up the hydrogen masers used as reference clocks for

VLBI sites in radio astronomy and geodesy. Good stability is required for averaging times up to a day, and this standard is much better than conventional Cs or Rb standards with performance close to that of the H maser to support the VLBI work. It fills a gap in the performance of standards available. We were impressed by the quality of work on the Cs cell clock. By suitable adjustment of buffer-gas partial pressures, the temperature- and power-dependent shifts can be made very small. There are two other reference Cs cells, one being used to stabilise the pump laser at 852nm. The laser is an Anritsu DFB device chosen for single-mode, mode-hop free operation. The fractional frequency stability is 3 parts in 10^{-14} at the flicker floor, from 1000 -10000s averaging time.

For discussions, we were joined by experienced Anritsu staff, who put to us the practical considerations in selecting instruments to manufacture. For example, their experience was that almost **all markets in the field under discussion, are likely to be niche markets**, and that even with the best academic or industrial guidance, the market might not materialise or be very large. The main topics discussed were microwave frequency standards, space and 1500-nm band optical communications equipment.

Ten years ago, Anritsu developed an acetylene-stabilised laser for sale as a frequency standard in the 1500-nm fibre band ready for the introduction of coherent communication techniques. However, the erbium-fibre amplifier was so successful, that no one needed to use coherent techniques, or the Anritsu standard. (This was a less-accurate device than that since developed using saturated-absorption techniques and seen at Chofu and Tsukuba during this mission). They also make an optical wavemeter (spectrum analyser) for the 1500 nm fibre band. Initially this was too accurate and too expensive. Now, however it is selling because the higher accuracy is needed. Present WDM optical channel spacings are coming down from 40 GHz to 12 GHz. This will require accuracy of about ± 100 MHz, i.e. 5 parts in 10^7 . Anritsu had experience of generating optical frequency combs with mode-locked lasers, they had also used a LiNbO₃ modulator to generate a comb that spanned 9 THz for a WDM point to point demonstration.

Anritsu's new caesium gas-cell frequency standard had been under development for about 8 years, but they were up against the received ideas of system designers, who thought in terms of the conventional Rb cell, Cs beam and H maser options. There was a specific application to backing up H masers at VLBI sites, but this comprised a small market. Dr Takahei said they were publishing papers at conferences, including the recent one at St Andrews, as a way of finding applications and customers.

In Japan there is an array of 100 stations to detect earth movements and this was calibrated by VLBI stations. VLBI works at 8 GHz, which makes it less sensitive to Japan's high humidity conditions than GPS. There were also 4 VLBI stations for Geodetic mapping. Anritsu did not make any GPS-related equipment. Anritsu was not working on optical frequency applications for space. For VLBI, the resolution was limited by fluctuations of the atmosphere, which are about 10^{-13} for 100s. The operators also need half a day's frequency hold in case of failure of the timing signal. The H maser is thus overkill, and the Cs cell standard about right. NASDA had little direct involvement – mainly providing the rockets. Anritsu was working on an H maser for space in collaboration with CRL. NASDA provides some money.

Anritsu staff asked how small ion traps could be made, as optical frequency standards, and whether we had plans for doing so. They mentioned that a promising application for ion traps and the femtosecond laser measurement system was in studying the fundamental constants, and asked whether a molecule, atom or ion would make the best standard.

3.4 National Metrology Institute of Japan (NMIJ), Tsukuba

3.4.1 Visit to NMIJ

NMIJ is a research institute of the National Institute of Advanced Industrial Science and Technology (AIST) which was reorganised in April 2001. At that time the former Ministry of International Trade and Industry (MITI) was replaced by the Ministry of Economy, Trade and Industry (METI). The former National Research Laboratory of Metrology (NRLM) under MITI became NMIJ under AIST and METI, with more independence.

One should note here that the scale of AIST is large, comparable perhaps with that of the once-tried British Ministry of Technology, having 5800 staff of whom 2500 are visiting. It links subjects such as IT, electronics, metrology, materials and machinery, as well as biotechnology, chemistry and geology. Industrial infrastructure technology (measurement standards, geological survey etc.) is linked to long-term/ high-risk technology (energy, environment, etc.) and to innovative technology (IT, biotechnology, etc.).

The NMIJ laboratory had recently moved into new buildings, including two underground floors, for better environmental stability. A team had visited NPL and received assistance on design at the time when NPL was planning its new buildings. An introduction was given by Dr Hirokazu Matsumoto, Deputy Director NMIJ, and we were shown around by Dr Atsushi Onae, see Photo 3.

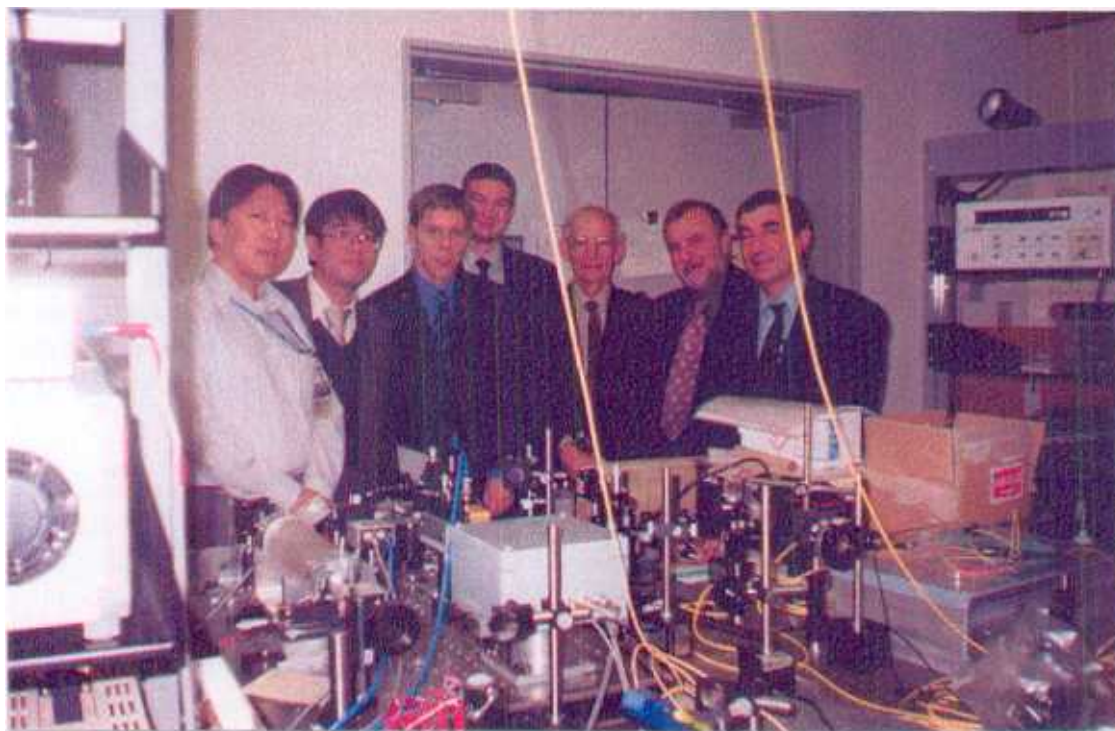


Photo 3: a wavelength standards laboratory of NMIJ: from left: Dr. Feng-Lei Hong, Dr Atsushi Onae, Dr Mark Plimmer, Mr Ivan Meakin (British Embassy), Dr David Knight, Professor Joshua Silver and Dr Hugh Klein

Dr Matsumoto discussed the question of international collaboration. One British scientist working in nanotechnology on a JSPS Fellowship had been there for 6 years. The Japanese government had decided to invite 10,000 foreign post-doctoral researchers. Foreign collaboration had become easier because the Japanese Government had passed over patent rights to individual researchers in the collaborations. Formerly, the government kept the patents.

Dr Atsushi Onae of the Time and Frequency Division, Wavelength Standards Section, showed us three well-equipped laboratories, and conversed briefly at the door of a fourth, containing microwave ion trap work. We saw a number of femtosecond lasers, three being Titanium-sapphire (Ti-sa) models used for frequency transfer and two more of the commercial (USA) mode-locked Er-fibre laser type at 1500nm.

Of the Ti-sa f-s lasers, H Inaba's laboratory, formerly Dr Sugiyama's, included a Giga-Optics model from the USA and two from Professor Krausz of Austria. A comb spanning 130nm was demonstrated. A fibre from Bath University, 5-cm long, was used to expand the output comb to an octave for absolute frequency measurement. The femtosecond laser comb at NMIJ was used to measure the frequency of iodine stabilised lasers, including the Nd-YAG/I₂ laser at 532 nm and also that of the 778 nm 2-photon Rb-stabilised laser, see below.

Dr Sugiyama commented that the system at Tsukuba has a prf of 150 MHz. It is an Austrian system, not based on prisms, bought from Prof. Krausz's start-up company. Also at Tsukuba, the 1 GHz ring cavity femtosecond laser was to produce a broader span of comb.

The commercial 1500-nm femtosecond lasers were demonstrated with a device made by Dr Fejer at Stanford, which generated third and fourth harmonic light in the green and blue, respectively. The pump diode light intensity controlled the f_{ceo} frequency, and a PZT element, in the cavity, was used to control the pulse repetition frequency.

At NMIJ, one type of optical frequency standard comprised a frequency-doubled YAG laser locked to iodine (YAGx2/I₂) in the green at 532 nm (Feng-Lei Hong and Jun Ishikawa, 2000). One of these, "Y1", had been developed to be transportable for making international comparisons, and had made a journey to BIPM in France and three annual journeys to the USA. Dr Feng-Lei Hong had worked in Boulder, USA with Dr John Hall, and had made an absolute frequency measurement against Cs with the femtosecond comb system, at the 300Hz level. The gas-cell affected reproducibility, with the same cell it was 300Hz and with different cells 5 kHz.

Another optical frequency standard was a 1550-nm band diode laser locked to saturated-absorption features in acetylene, similar to that seen in Dr Nakagawa's laboratory at the University of Electro-communications, Chofu, above. The 1500-nm f-s lasers, mentioned earlier, were used to extend the range of calibration of this laser for optical communications in the erbium-fibre amplifier band, 1530-1570 nm. Absolute frequency measurement was via mixing the 2nd harmonic with the fundamental of the 778-nm rubidium stabilised laser.

We heard that an ⁸⁷Sr⁺ ion trap apparatus for observing the 5 GHz ground state hyperfine transition was under development at NMIJ. About 10⁶ ions were trapped in a 40-mm diameter hyperbolic trap. Lasers at 422 nm and 1092 nm (fibre) were used.

3.4.2 Discussion at NMIJ

Dr Matsumoto pointed out that only 3 out of 250 calibration requirements needed optical frequencies. Dr Minoshima said that in her Ph. D. days the femtosecond laser had filled a whole room: it was interesting to see it progress towards a portable instrument. She said that instead of Ti-Sa, a gain medium should be sought that could be pumped directly by a diode laser (instead of by a frequency-doubled YAG pumped by a diode laser), such as Cr:Li:SAF.

Dr Onae said that in terms of finding markets for ultra-accurate systems, there was the idea of building “demonstrators”. They had once been asked for an example of a stabilised laser by NTT so that NTT could explore how to use it. In general the study of fundamental subjects and the advance of knowledge was important.

Dr Hong asked what existing applications we saw. In terms of an optical clock, it could lead to an “alternative realisation” of the second (CCTF, earlier this year), and because of its higher stability (10^{-15} in 1s), promised a potentially better primary standard for a future redefinition of the second. Dr Hong suggested that in a portable optical frequency system the vibration isolation of the optical reference cavity (used to obtain a narrow laser line) might be achieved by an active system, for compactness.

3.5 The Femtosecond Technology Research Association of Japan (FESTA), Tsukuba

FESTA represents a consortium of commercial companies and receives government funding via the New Energy and Industrial Technology Development Organisation (NEDO) for a fixed-term technology development programme, on very fast processes. It included medical low-damage investigation. Of the companies in the consortium, only one, Matsushita Electric Corporation of America was not Japanese. There was not a specific programme on optical frequency measurement.

Dr K Asakawa, leader of the 1st Research Unit, gave the introduction. The work of the laboratories was in two time phases: 1995-2000, and 2000-2004, they were into the second phase, towards realisation of some devices.

One FESTA project involves the use of a femtosecond laser interacting with an electron beam to generate a short pulse of X-rays for in-situ monitoring of moving turbine blades. This uses the inverse Compton effect, by briefly “wiggling” a relativistic electron beam. They had established the principle, and now were trying to reduce the size and energy consumption of the device to turn it into an instrument. We would have been more interested had the X-rays been coherent and related to the f-s optical input radiation, but this was not thought to be so.

Other FESTA experiments were aimed towards terabit/s pulsed optical fibre communication techniques. In the communications field, the target had risen from 100 Gb/s to 10 Tb/s in 5 years. This could be achieved using 1000 channels by wavelength division multiplexing (WDM), combined with optical time-division multiplexing (OTDM) at 10 Gb/s on each channel. The femtosecond lasers could produce the set of sidebands for the WDM channels and were also involved in experiments to produce, maintain and switch short pulses propagating through fibres. There was an emphasis on optical-node devices for all optical multiplexing and demultiplexing of signals.

Dr K Ogawa, unit leader (pulse propagation and propagation technologies), showed us the laboratories. He had worked for two years at Cambridge with Hitachi in collaboration with the Cavendish Laboratory, see Ogawa et al. 1995. We saw 4-wave mixing using a DFB laser for

conversion of a 1563 nm signal to 1543 nm at the same pulse width (about 610 fs). There was also a demonstration of a potentially low-energy quantum-well pulse switch using two normally-cut fibre ends being used to couple in and out of small multiple quantum well (MQW) strips on a substrate. They were trying for a gating energy of 100fJ per pulse at 1500nm, but were working at 20 pJ. An OPO f-s system working between 1300-1500 nm was mentioned in connection with this work. See the papers received: Ogawa and Matsui 1999, and Ogawa and Pelusi 2001.

3.6 Communication Research Laboratory (CRL) at Koganei

We were greeted by Dr Mizuhiko Hosokawa and shown three laboratories, broadly covering Japan Standard Time (Tsukasa Iwama), time and frequency measurements, and atomic frequency standards and clocks. Towards the end of the visit there was a discussion, in which primarily Dr Takao Morikawa, Dr Michito Imae and Dr Masatoshi Kajita took part. This was an impressive visit, close to our interests and several topics were carefully discussed. The work of the laboratories was close to that performed at NPL, with additional involvement of radio astronomy and space activities.

3.6.1 Lab 1: Japan Standard Time Group

At CRL, a group of 10 Hewlett Packard 5071A caesium clocks were maintained in controlled temperature and humidity conditions to provide Japan Standard Time. Different displays read out the JST, UTC and TAI timescales. A very large display, perhaps 1m high, read out JST at the top of the front face of the main CRL building. There were frequent time comparisons with other laboratories, mainly via the BIPM-organised common-view schedules for observing GPS satellites. CRL is a central laboratory in the Asia/Oceania region for comparisons. Every five days the readings of all ten clocks are reported to BIPM, as a contribution to compiling the world UTC timescale to which national laboratories' scales are connected in the regularly published BIPM "Circular T".

Dissemination of time to Japan was via a telephone service, now 10 years old, an internet service to start next March, now under test and new VLF coded radio broadcasts from which automatic radio clocks and watches and other services can take the time.

Frequency calibration (carried out under the ISO 17025 norm) was available via a digital computer link. Accuracies requested were typically 1 part in 10^9 to 10^{10} , although the service was available at 1 part in 10^{13} .

3.6.2 Lab 2: Time comparisons

CRL used GPS carrier phase for increased time-comparison accuracy, and also took part in 2-way time transfers with other laboratories via telecommunication satellites in the 10-12 GHz bands, as do other major national laboratories. They were also concerned with stabilisation of the timescale, e.g. at 10 MHz.

They observe pulsar timing, using the Kashima 2.2 GHz facility, 1 day per week. The pulsar, PSR1937+21, showed a stability going to few $\times 10^{-15}$ at 1000 days, thus offering scope to check the absolute stability of TAI. Such rotating neutron-star pulsars did not show the "glitches" observed from binaries, so it was a potentially useful form of astronomical clock, see Audoin and Guinot 2001.

Satellite navigation systems such as GPS, GLONASS and the proposed European Galileo

system were discussed. Japan had programmes to keep abreast of the technology, but those present saw no need for a further system per se. On augmentation (to improve accuracy) of GPS – there was MSAT, next year. They had a programme TCE (Time Comparison Equipment) which at present used satellite ETS-8.

In 2004 a Japanese test satellite will be launched, carrying a US-made Cs clock, managed by NASDA, arising from a decision made 4 or 5 years ago. CRL have a collaboration with Anritsu (see above) to make a space H maser, but there were no plans to fly it yet. The design was finished at CRL (M Morikawa) and Anritsu were to build it. The target specification was <60 kg weight, <100W power demand and 10^{-14} stability. There was a mix of government and Anritsu funding.

3.6.3 Lab 3: Primary Cs microwave time standards at CRL

CRL's optically pumped Cs beam standard was operating and contributing to UTC, one of a handful in the world. There is a Cs laser-cooled atomic fountain apparatus, which was large, and in an advanced state, but not yet in operation as a standard. The vertical alignment of the launch was being worked on. The room's ceiling was high, about 4-5 m, allowing removal of the magnetic shields by lifting off, for making adjustments. (There is another Cs fountain apparatus, at NMIJ, but we were unable to see it). These fountain primary standards, following developments in Paris by Clairon et al. (see Lemonde 2001), allow realisation of the second to 1 part in 10^{15} , almost a factor-10 advance on other types of Cs clocks – see Audoin and Guinot 2001, and are being developed at major national laboratories.

3.6.4 Discussions at CRL on future prospects

At CRL the ion trap experimental work was at the Kansai branch, led by Dr Watanabe, in collaboration with Dr Urabe, the University of Osaka. Dr Urabe was studying Ca^+ . Microwave transitions in Zn^+ and Cd^+ were being studied at Kansai. Dr Kajita gave us two papers, on the theory of molecules in traps, Kajita et al. 2001, and on laser cooling of atoms, Kajita and Morikawa 1999. As regards optical standards, they were starting a **feasibility study, which would be done at Koganei**. The optical clock work would be done in cooperation with the Kansai group. As to whether an ion or atom would be selected, they did not know, hoping to try different ions or atoms before making a final selection. Their approach to optical frequency standards was to first establish measurement of optical frequencies and then to look at the possibility of a better standard than Cs in the optical, for which there were the feasibility studies.

For future measurements of an optical standard, CRL had a good local microwave measurement standard: UTC (CRL) offered 10^{-15} over 1 year and its traceability to TAI and UTC was very good. They also had two H masers and the Cs fountain.

Staff at CRL were against a “mise en pratique” for the definition of the second, analogous to that used for the metre (in which different standards are allowed equally, subject to their given accuracy). They prefer the wording “secondary representation of” where the unit of time is derived from a non-Cs source.

For optical fibre communications at 1550 nm, CRL had to support the ITU grid (193.1 THz anchor, 100GHz spacing, 12.5 GHz in future). The accuracy range required at present, was 5 digits in the field, 7 digits for manufacturing and 9 – 10 digits for international standards.

Asked about better clocks for GPS and similar systems, for reliability and accuracy, CRL staff

thought Japan was behind the USA and ESA with respect to space. Japan makes a good rubidium standard, but otherwise has little to contribute to a space clock. Regarding the economic importance of such things, the National Space Development Council said 3 or 4 years ago that Japan should establish the key technologies for satellite navigation. Following guidelines they started research towards the 2004 launch, by NASDA. CRL staff felt Japan should not have its own satellite navigation system: there were already enough such systems existing or being planned. They thought the market for space clocks was small. Possible collaboration was discussed. It was felt this would be potentially difficult, as Japanese and European companies might be in competition, particularly in space matters. However, there was general interest in forming partnerships with UK companies or research organisations.

There are 10 VLBI sites in Japan, 4 for calibrating the GPS 1000-point geophysical network on the main island. There were also 4 new astronomical stations for the Radio Star Measurement project, but the market for clocks was expected to be small.

3.7 Nippon Telegraph and Telephone Corporation (NTT) Laboratories at Yokosuka

This was a large ten storey building reminiscent of the Bell Laboratories building at Holmdel, New Jersey. The visit was to the NTT Network Innovation Laboratories. We were given a brief introductory talk by Dr M. Kawachi, Group Director, Dr S. Kawanishi and Dr T. Morioka. In the laboratories we also met Takashi Yamamoto and Kunihiko Mori. The notes below are supplemented by 7 papers received.

The work we saw at the NTT laboratories was looking ahead from the present barely established WDM transmission systems, carrying perhaps 30 or 50 channels. Options exist either to use optical time division multiplexing (OTDM) using time-interleaving of pulse trains to give Tb/s pulse rate in the fibre, or by using fibre-enhanced spectral spreading of e.g. 10-GHz-spaced sidebands to provide 1000 or so separate channels in dense wavelength division multiplexing (DWDM).

In either case, the mode-locked laser output has its pulse shortened and its sideband spectrum spread by amplification followed by self mixing in fibre. This is similar to the process used to obtain octave comb spread in the Ti-sapphire lasers used for optical frequency measurement, and considerable effort in the telecommunications community has gone into designing and using fibers with special dispersion characteristics for the 1500 nm band. Details of NTT research are in the papers by Mori et al. 1997, Tamura and Nakazawa 1999b and Yoshida and Nakazawa 1998.

3.8 Summary Tables

A summary of **applications** of optical frequency measurement is shown below in **Table 3**. The accuracy requirements span 9 orders of magnitude, but even the most demanding requirement is within the range of extrapolation from published work, see Knight 2001.

The range of subjects discussed above is in **Table 4: Topics**. The upper part of the table concerns optical subjects and the lower part shows microwave, RF and timescale items. These are connected with measuring the optical standards in terms of the SI units, the second and the hertz.

Details of the various **femtosecond lasers** encountered are in **Table 5**. These provide the “clockwork” to link optical standards to RF and microwave signals and clocks. See for example Diddams, Udem et al. 2001 and Cundiff et al. 2001.

Matters concerned with commercial exploitation are shown in **Table 6: Instruments and Markets**. This is presented in the order of the visits and contains a mix of actual experience and new opportunities.

Table 3: Applications of Optical Frequency Measurement

Application	Method etc.	Accuracy	Date	Notes
optical tele-communications	optical fibre	10^{-7} in the field	2002	DWDM at 1300-1500 nm
sub-mm radio astronomy rx	optical difference f	10^{-7} at sub-mm	2005	f-s comb to calibrate
lab length stds	trapped ions etc	up to 10^{-14}	current	for “mise en pratique”
time variation of fundamental constants	compare different high-accuracy f stds	10^{-14} or better	current	test theories of physics
redefinition of the second	trapped ion or similar +fs laser	10^{-16} or better	c2010	need to run optical “clock” reliably first

3. Notes: rx: receiver

Table 4: Topics

Topic	Institute	doing: D using: U	Work Nature	state	Institute role	Application
Optical f standards	U Chofu	D		atom studies		study atoms etc
	U Kyoto	D	fund. res	starting, xfer from NMIJ	academic	test theory
		D	metrology	cell stab.laser trapped atom	nat stds	length stds
		D	metrology	feas. study	nat. stds	t&f stds
F-s lasers	U Kyoto	D	fund. res.	home-made	academic	measure ion trap
		D,U	laser f meas.t	have 5 used for 3 f meas.ts	nat.stds	length stds 532, 633 & 778 nm;
	ESTR	D,U	X-ray source	4y to end	tech. dev	turbine monitoring
		D,U	pulse train, f comb 1.5µm	dev.t res.	t/com res	t/com system
Ion traps	U Kyoto	D	Yb ⁺	starting	academic	fundamental res. test theory
	NMIJ	D	Yb ⁺	remaining system	nat. stds	length/t&f stds
		D	metrology	feas. study	nat.stds	t&f stds
1500 nm f standards	U Chofu	D	prototype	ready,10 ⁻¹⁰	applied research	factory cal
	NMIJ	D	bench std		nat. stds	int.l comp.
	CRL	D	f std	maintain 10 ⁻⁹ –10 ⁻¹⁰	nat. stds	telecomms
		U		< 10 ⁻⁷	t/com dev	telecomms
microwave f standards	Anritsu	D	Cs cell std	prototype	dev. & mfr	VLBI maser backup
	CRL (+Anritsu)	D		completed	design	space technol. expt., reduced
	Anritsu (+CRL)	D	H maser	starting	develop & build	size
cold atom	CRL	D	Cs fountain	experiment	nat. std	t&f stds
	NMIJ	D	Cs fountain	experiment	nat. std	t&f stds
Ion traps	NMIJ	D	⁸⁷ Sr ⁺	experiment	nat. stds	t&f stds
	CRL	D	Zn ⁺ , Cd ⁺	experiment	nat. stds	t&f stds
time scales	CRL	D	metrology	continuous	nat. std	Jpn Std Time, TAI, UTC
	NMIJ	D	metrology	continuous	nat. std	TAI, UTC

Notes: dev.: development; feas.: feasibility; nat.: national; res.: research; std.: standard;

Table 5: Femtosecond (f-s) Lasers

Entry no.	Place/lab	S/D *	make	prf /MHz	pump	pulse /fs	notes assoc.fibre etc.	used for etc.	f ref. used
A: Titanium-sapphire, 350 THz (~850 nm centre); octave comb spread (with fibre)									
1	Kytoto U.	D	home-built, 2 prism	100	to acquire			fundamental science	Rb + GPS
2	NMIJ	D,S	Krausz OL-19? Austria	150	4.8W Verdi	10	Bath U fibre;	optical f measurement	Cs
3	NMIJ	D,S	Giga Optics (USA)	1000			ring, chirped mirror dispersion compensation	optical f measurement	Cs
4	FESTA	D		10 Hz		80		400fs,2.33keV X-ray pulse	
(5)	NMIJ	D	Menlo Systems (Germany)				included	commercial kit; optical f meas.t (mentioned by us)	usually Cs
B: Er-fibre, 190 THz (1560 nm centre)									
1	NMIJ	S,D	IMRA (USA)					optical-fibre band f standards	C ₂ H ₂
2	NTT	S,D	polarising Er fibre MLL	10000	1480 nm	2700	Sumitomo fibre, for compression	ultrafast OTDM	wavelength
C: other: mode-locked diode laser (~1550 nm centre)									
1	FESTA	D	OKI InP diode laser	500000	dc	~1000	fibre for compression	ultrashort-pulse OTDM	wavelength
2	NTT	S,D	s/c diode laser 600um long?, MLL+amp+fibre	20000	dc		non-uniform fibre, decreasing dispersion	s/c lightwave source 100-1000 lines to fit ITU grid?	
3	NTT	P	diode laser MLL+amp+fibre	12500	dc	~1000	Ditto	DWDM 1000 channel source, Takara et al. 2000	C ₂ H ₂ or ≡, at 1 point

*Notes: D: discussed; P: in paper; S: seen in use; s/c: semiconductor

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Table 6: Instruments and Markets

Mic. /opt.	Lab	Device	Year(s)	Market, result	note
O	Anritsu	early C ₂ H ₂ stabilised laser	c1991	medium: for optical networks; did not sell	coherent communications did not happen (at 1550 nm)
O	Anritsu	opt. spectrum analyser (10 ⁻⁷)	current	medium: for optical networks; now selling	initially too expensive & too accurate; now about right for market
M	Anritsu	laser pumped Cs cell standard	new	small: as back-up for VLBI H masers	prototype developed; seeking applications
M	Anritsu	H maser	c2004/5	small: for space programme	new development with CRL/NASDA
R	CRI	radio clocks	2001 on	large: consumers & utilities; sales of receiver clocks	for new transmitters at 60 kHz and 40 kHz in Japan
O	ILS, Chofu	sat. absorption C ₂ H ₂ stabilised laser (10 ⁻¹⁰)	ready now	small: factory bench calibrator, for future DWDM at 1550 nm;	prototype developed; seeking a manufacturer
O	NMIJ	special fibre to give octave comb at 850 nm	2000 on	small: scientific market; research product	using U, Bath, also Mitsubishi Cable? Sumitomo?
O	NMIJ	demonstrator items (lasers)	suggested	pre-prototype	for industry (potential users) to try out
O	NTT	f meter, 10 ⁻⁷ or better, needed	2001-2	medium: for optical networks; DWDM at 1550 nm	existing spectrum analysers not good enough

Notes:

(i) DWDM: dense wavelength-division multiplexing; NASDA: National Space Development Agency of Japan; sat.: saturated; VLBI: very long baseline interferometry.

(ii) University professors can now head their own companies in Japan.

(iii) Patent rights now go to individual researchers in collaborations; they are no longer retained by the Japanese government.

3 GENERAL OBSERVATIONS AND SCOPE FOR COLLABORATION

4.1 General Observations

We found that the importance of the new femtosecond laser technology for directly measuring optical frequencies was already appreciated in Japan. The technique was already in use or under active consideration at the two national metrology laboratories, NMIJ and CRL, and the technology was being transferred to the University of Kyoto.

The other main area of technology involving optical frequency measurement and the use of femtosecond lasers was in optical-fibre telecommunications systems. For this, adequate frequency standards had been developed at the University of Electro-Communications, Chofu, NMIJ and CRL, and were to be maintained at NMIJ and CRL. Erbium-fibre f-s lasers are being used for (a) generating trains of short pulses, or (b) generating “combs” of carrier signals to fit parallel communication channels. In the first application, the fibre laser seemed to be giving way to semiconductor mode-locked lasers, some repeating at frequencies as high as 500 GHz, partly because the fibre laser was considered too big for use in quantity at switching centres. These in turn can produce pulse lengths in the high hundreds of fs, which can be shortened in solid-state or waveguide structures.

We encountered only one instance of X-ray production at FESTA, but this was not a coherent source. The idea of extending optical wavelength standards by some coherent process such as harmonic generation beyond the uv into the X-ray region, to give better than existing standards, remains open to future scientific advance. X-ray spectra of highly-ionised atoms at the Chofu EBIT might lead to the development of new standards.

Work on femtosecond laser combs – at NMIJ (AIST) appears to be at a similar stage to UK projects. Optical frequency standards based on ions and cold atoms are less advanced. However, they seemed to be informed and looking ahead e.g. in metrology.

The scientific work was competitive; some labs were very well equipped, more so than in the UK. There was heavy investment in engineering applications at FESTA. We also noted care and attention to detail, for example, going into the construction and study of the caesium gas-cell frequency standard prototypes at Anritsu.

Comparing the relevant Japanese R&D with that of the UK, Japan puts more effort in and the workers are good, perhaps better in technology. However, in general, the long-term aims in Japan seemed more limited to “what industry says it wants”. We noted close technical collaboration between different labs and organisations in Japan.

Within Japan there were good links between scientists working in the same area. There have been political difficulties in the past (e.g. different ministries sponsoring work), which may have led to duplication of work and lack of formal collaboration. New frameworks may try and reduce this and make them more competitive.

One of Japan’s strengths is that the government funds really well when they decide to. There are some excellent basic research projects and they have quality researchers to carry them out.

Work on optical frequency or wavelength standards and measurement in Japan is mostly strong but fragmented. With more focus it could be stronger. They appear to be behind on developing ion trap based optical frequency/wavelength standards.

Table 7: UK Collaborations with Japan
encountered/ relating to area of research covered

	Dates	Item known to us	Organisations		Duration years	Funding	Notes
			From	To/with			
PAST	1960-1970s		NLRM	NPL	0.5 - 1	home lab	Time & frequency
	1987	secondment	NPL	ETL, Tsukuba	4 months	home lab	Josephson junction
	c1992-1995	secondment?	Hitachi	Hitachi Lab. Cambridge	2.5	company	collaboration:Cambridge University
2. PRESENT & ONGOING	1996-2001	ICORP	NPL & Oxford U.	JST/UEC, Chofu	5	50:50	trapped ions
	2001-	JST Fellow	UEC, Chofu	Oxford		JST	trapped ions
	c1995	Fellow	UK	NMIJ, Tsukuba	6+	JSPS	nanotechnology
3. FUTURE		visits to UK	Japan	UK	weeks	British Council	
		study visits & research	Japan or UK	UK or Japan	months - years	Royal Society with JSPS	usually reciprocal; fellowships>6 mths
		post-docs	rest of world	Japan	?	AIST(NMIJ)	numbers increased
		new ICORPs	rest of world	Japan	5	50:50	continue

Notes: ETL: Electro-Technical Laboratory; JSPS: Japan Society for Promotion of Science; UEC: Univ. of Electro-communications

The level of contact and informal linkage between different labs and companies was strong. The large size of the FESTA programme and its timescale (10 years), all planned carefully and with targeted objectives was impressive. Nonetheless it was difficult to really get to the bottom of the motivation of research projects in Japan.

4.2 Opportunities for UK-Japan collaboration

At the individual level, there are a number of different schemes to enable exchange of researchers between the UK and Japan including fellowships to Japan for between 3 months and 2 years. At the project level, there are a few schemes. Examples of two that originate in Japan are:

The New Energy and Industrial Technology Development Organisation (NEDO) in Japan has an International Joint Research Grant Program which funds a team of collaborators to work in particular areas including International Standard Development.

The Japanese Science and Technology Corporation (JST) set five year International Cooperative Research Projects (ICORP). The UK has been involved in two ICORPS, the most recent being the 1996- 2001 “Cold Trapped Ions” project.

Some examples of collaborations between the UK and Japan and funding mechanisms are shown in Table 7.

From the perspective of UK researchers these schemes might be a way of enhancing existing projects by collaboration, but there is no specific mechanism for UK government funding to match the Japanese contribution.

The British Embassy in Tokyo has an active team headed by Dr Mike Norton (Science and Technology Counsellor) to help facilitate communications and contact but there appears to be no UK based schemes to fund joint projects of significant size. Specifically in the optical clock and optical frequency standards and measurement area, staff at NMIJ seemed interested in collaborating with the UK. We heard that the AIST was interested in promoting international agreements.

5 CONCLUSIONS

The “Trapped Ions for Measurement and Enterprise (TIME) scouting mission to Japan in November 2001 was able visit a number of government and industrial organisations which had an interest in optical frequency standards and measurement. Ion-trap based optical frequency standards are not as developed in Japan as in the UK, but femtosecond laser comb work has been making rapid progress at NMIJ. Work there and at other Japanese laboratories has also concentrated on less accurate optical frequency gas cell standards. Work is divided between several national labs, universities and companies in Japan, whereas the focus in the UK is at NPL.

Staff at Anritsu were worried that the limited VLBI market would not be large enough to sustain the Cs microwave standards they are developing. CRL staff discussed the possibility of “secondary representations of the second” recognising that this might be a driver for optical clocks and optical frequency standards.

There is a chance for the UK to lead in the development of optical clocks, since the constituent techniques are being developed within one organisation (NPL), whereas in Japan two organisations are involved (NMIJ and CRL at two geographic locations). Also single trapped ion optical frequency standards still need considerable further development in Japan.

There are a number of other more detailed observations and conclusions

The measurement opportunities offered by femtosecond laser comb technology were widely appreciated by scientists in Japan.

Many of the laboratories we visited were very well equipped, in some cases better than those in the UK. For example NMIJ already had 5 femtosecond comb systems.

A feasibility study on optical frequency standards and clocks was being started at CRL Koganei; future work would be likely to involve collaboration with the ion trapping researchers at the Kansai branch. The long-term direction of this work might well be towards optical clocks, however, this concept is still at the planning stage.

Staffing levels at some laboratories seemed low.

Ministerial structures in Japan may have blocked formal links and collaborations within Japan in the past but now there were several examples of good technical links. Recent reorganisations may have helped address this issue.

There are many Japanese government initiatives to encourage collaboration with other countries, for example JST's ICORP projects and NEDO International Development program projects, which must involve foreign collaborators. One problem with trying to join these programmes is that on the UK side there is relatively little direct support for international research collaborations. Brian Ferrar (at the British Embassy in Tokyo) is keen to help foster further collaborations and to facilitate the signing of agreements between the AIST and the UK. The UK government might consider introducing schemes to fund joint projects of significant size. Interest in possible collaboration or partnership with the UK in the area of optical frequency measurement and standards was expressed by a number of Japanese researchers, for example at NMIJ and CRL.

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LIST OF ACRONYMS AND ABBREVIATIONS

	National Institute of Advanced Industrial Science & Technology, Japan
BBSRC	Biotechnology and Biological Sciences Research Council, UK
	Bose-Einstein Condensation
BIPM	Le Bureau International des Poids et Mesures, Sèvres, France
BNSC	British National Space Centre
C ₂ H ₂	acetylene
	The Consultative Committee for Time and Frequency of the CIPM
CIPM	Comité International des Poids et Mesures
	Communications Research Laboratory, Japan
	dispersion compensated fibre
	dispersion shifted fibre
	Department of Trade and Industry, UK
DWDM	dense wavelength division multiplexing
	electron beam ion trap
EPSRC	Engineering and Physical Sciences Research Council, UK
ERATO	Exploratory Research for Advanced Technology, of JST
EU	European Union
	European Space Agency
ETS-8	Japanese Engineering Test Satellite no. 8
	carrier-envelope-offset frequency (of femtosecond laser comb)
FESTA	The Femtosecond Technology Research Association, Japan
FSTP	Femtosecond Technology Project, Japan
Galileo	1: spacecraft to explore the moons of Jupiter (NASA/JPL) 2: proposed EU global satellite navigation constellation (applies here)
GLONASS	Russian satellite positioning system, similar to GPS

	Global Positioning System, USA
	helium -neon (laser)
ICORP	International Cooperative Research Project, of JST, Japan
	Institute for Laser Science, University of Electro-Communications, Chofu
	International Organisation for Standardization
	International Telecommunications Union, Geneva
	Joint Institute for Laboratory Astrophysics, University of Colorado and NIST at Boulder, USA
JOSA	Journal of the Optical Society of America
	Japan Society for the Promotion of Science
JST	Japan Science and Technology Corporation
JPL	Jet Propulsion Laboratory, USA
	light amplification by stimulated emission of radiation
maser	microwave amplification by stimulated emission of radiation
ME	Ministry of Economy, Trade and Industry, Japan
	Massachusetts Institute of Technology, USA
	Ministry of International Trade and Industry, Japan, replaced by METI
MQW	multiple-quantum-well (semiconductor device)
MSAT	North American broadband communications satellite
NASA	National Aeronautics and Space Administration, USA
NASDA	National Space Development Agency of Japan
NEDO	New Energy and Industrial Technology Development Organisation, Japan
Nd-YAG	neodymium-yttrium aluminium garnet (laser)
NIST	National Institute of Standards and Technology, USA
	National Metrology Institute of Japan
NRLM	National Research Laboratory of Metrology of Japan, now in NMIJ
N	Nippon Telegraph and Telephone Corporation

	optical clock
OPO	optical parametric oscillator
OTDM	optical time domain multiplexing
prf	pulse repetition frequency
	Physikalisch-Technische Bundesanstalt, Germany
	posts, telegraph and telephones (organisation)
	radio astronomy
	single mode fibre
	International Atomic Time
	Time Comparison Equipment (CRL)
TDM	time division multiplexing
TIME	Trapped Ions for Measurement and Enterprise
UK	United Kingdom
	University of Electro-Communications, Chofu
	United States of America
UTC	Universal Coordinated Time
VLBI	very long baseline interferometry
WDM	wavelength division multiplexing
YAGx2/I ₂	frequency-doubled Nd-YAG laser locked to iodine

APPENDIX NPL Press Release PR40-2001, 27 November 2001:

- "UK-Japan "Cold trapped ion" Collaboration Celebrates Fifth Successful Year"



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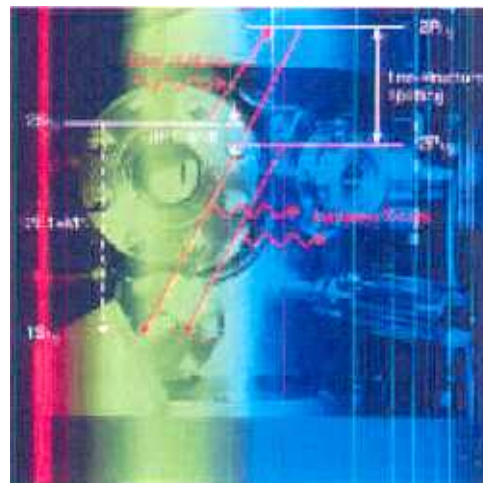
PRESS NOTICE

UK-JAPAN "COLD TRAPPED ION" COLLABORATION CELEBRATES FIFTH SUCCESSFUL YEAR.

The UK-Japan, "International Cooperative Research Project" (ICORP) between the UK National Physical Laboratory (NPL), the University of Oxford and the Japanese Science and Technology Corporation (JST), celebrates its fifth birthday this month with two symposia.

On 27 November at the British Embassy, Tokyo a symposium on **"Cold Trapped Ions"**, includes research reports on world leading developments:

Highly accurate (below 1 in 10^{13}) optical frequency measurements of transitions in singly charged laser-cooled trapped ions using femtosecond laser combs at NPL. Optical clocks based on these devices will eventually be superior to the best microwave clocks, with new ways of realising the second*. Optical clocks were the subject of a recent prize-winning poster at the UK House of Commons#.



The first observation at the University of Oxford of the Lamb shift in one-electron ions of nitrogen in an "Electron Beam Ion Trap" (EBIT) using high power IR laser resonance. Accurate measurements of the Lamb shift will test quantum electrodynamics (QED).

Dr M D Plimmer will contrast optical frequency standards based on molecules, atoms and ions.

The latest results from the Tokyo EBIT including, X-ray and UV spectra of highly charged ions (HCIs) and the study of HCl-surface interactions.

The second symposium on 28 November entitled "**New Trends in Atomic Physics**" at Tokyo's National Museum of Emerging Science and Innovation has an impressive line-up of Japanese speakers including Professor Arima (Japan, House of Councillors). On the British side, Professor J D Silver, the UK ICORP research director (University of Oxford) will describe QED experiments. Dr H A Klein (NPL) the UK ICORP research deputy director will describe optical clocks based on trapped ions and potential applications of very-stable lasers in space. Dr D J E Knight will review precise frequency measurements for fundamental constants. Professor S Ohtani the Japanese ICORP research director, will outline exciting applications of HCIs.

A video of the "Cold Trapped Ion" ICORP research will be released early in 2002. The celebrations in Tokyo will be attended by senior British scientists and UK government officials. Discussions with their Japanese counterparts will centre on the new directions identified for ion trap based research, and future UK-Japanese partnerships in atomic physics and metrology.

* Proceedings of the 6th Symposium on Frequency Standards and Metrology, St Andrews September 9-14, 2001, (World Scientific) ed. P Gill, in preparation.

http://www.npl.co.uk/npl/length/wss/projectintros/poster/keeping_time_with_a_single_atom.pdf

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