

THE NATIONAL PHYSICAL LABORATORY

**Final report to the European Space Agency (ESA) from the National
Physical Laboratory (NPL)
ESTEC contract 13290/98/NL/MV**

**A study of ultra-stable optical clocks, frequency
sources and standards for space applications**

**Hugh A Klein
David JE Knight**

October 1999

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ISSN 1469-4921

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A handwritten signature in black ink, appearing to read 'D. Robinson', with a stylized, cursive script.

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EXECUTIVE SUMMARY

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This study has examined the potential stable laser requirements for a range of space applications. An interim report was presented in the form of a conference paper summarising our initial findings (see Appendix 5). This final report gives our conclusions in more detail and recommends areas for further study.

Optical or laser-based communication systems are expected to supplement microwave based systems for satellite-to-satellite and spacecraft-to-satellite communications early in the next millennium. Optical systems can carry far more traffic than microwave and address the need to increase communication bandwidths to meet the demands of commerce and the entertainment industry. There is already significant research and commercial interest in this area (now driven particularly by the multi-media and Internet services delivery sector) and there is a strong need to establish which are the best choices of optical sources to develop for space based optical communications. In addition to communication requirements there are strong arguments for developing ultra-stable optical frequency sources and detectors in space for at least two other purposes. At present the microwave radiation that is used for communications is also used for other purposes, for example navigation or tracking, and "space science" experiments. With the switch from the microwave to the optical for communications it may well be convenient to switch to the optical for these and other functions.

A number of optical systems are already planned or are being developed for future space applications. Some of these will require ultra-stable or narrow laser sources. Examples include:

- High data rate communications for the Internet and multimedia applications at Gigabits per second using coherent detection which needs stable local oscillators.
- Detection of gravitational waves with frequencies below one Hz

Further study is required to assess the suitability of the likely components for these and other applications. The basic building blocks are solid state and a number of the components have been successfully assessed for space qualification or flown already.

This report discusses potential space applications of stable lasers and highlights the following areas for further more detailed study:

- Coherent communications - commercial intersatellite links
High-bandwidth multimedia/Internet driven intersatellite links are being developed which will require narrow lasers with kHz to MHz linewidths. There has already been

significant work in this area which should be continued with space based demonstrations. The requirement for absolute optical frequency standards in this area is undefined at present and will depend on the laser systems finally adopted - many of the developments (and the debate between direct and coherent detection) are commercially sensitive. Frequency-doubled iodine stabilised Nd:YAG lasers are one option which has already been demonstrated.

- Coherent communications - deep space

The trade off between the pulse position modulation and coherent detection methods for deep space needs further examination; the requirements for “space science” and navigation need to be taken into account.

- Space interferometry e.g. gravitational wave detection

It would be useful to validate the scheme for laser frequency noise reduction proposed in the LISA (Laser Interferometer Space Antenna) pre-phase A report. An ESA intended invitation to tender suggests investigating the capabilities of Nd:YAG lasers with mHz stabilities. This is certainly an area worthy of further development as the desired laser specification is beyond that presently achievable.

- High stability timescales related to optical clocks

“Optical clocks” for improved time standards, might be used for example as part of the deep space network or ultimately for an improved global navigation system. The laser cooled ion trap based systems are a good choice for further study. They offer the opportunity to improve the stability of timescales beyond those achievable using microwave standards.

There are several areas of interest to ESA which may require stable lasers in the future. At present no-one has a formal co-ordinating role, although a recent IITT 98.1XA.12 suggests that “core laser technology development” will be addressed in the near future. ESA has recognised that there are common background laser requirements for different programmes. We welcome this approach and would encourage such co-ordinated developments, with the promotion of suitable groupings of experts and subjects areas as ESA establishes how best to move forward and develop its strategy and activities in the field of optical frequencies for space.

- International links between scientists and engineers could be further strengthened by the promotion of joint projects in the emerging field of optical frequencies for space.
- A detailed analysis of potential laser based projects which could be proposed for later phases of the international space station is needed.
- We suggest holding a workshop (of one or two days), sponsored by ESA to bring together representatives of all parties in Europe with an interest in stable optical frequencies for space applications. One of the outcomes of such a workshop could be the formation of a “club” of organisations interested in stable laser sources and standards for space. Benefits to ESA would include spin-in of ideas through a central point of contact, newsletters and information updates via email.

Table of contents

EXECUTIVE SUMMARY	iii
1. Introduction and the move from microwave to optical	1
1.1 Optical developments over the last few decades	2
(i) Industrial applications.....	2
(ii) Military developments.....	2
(iii) Scientific research	2
1.2 The impact of optical developments on space applications	3
(i) Communications.....	3
(ii) Ranging and Tracking	4
(iii) Science	4
1.3 Stability, linewidth and accuracy issues	5
2. Potential space applications of stable lasers	7
2.1 Communications.....	7
2.2 Navigation, tracking and timing	8
2.3 "Radio" and "Light" Science	8
2.4 Space applications of accurate frequency standards and clocks	9
3. Optical Technology for space applications	11
3.1 The move from micro-wave to the optical for communications.....	11
3.2 Coherent and direct detection for laser communications in space	12
3.3 Laser linewidth requirements for coherent communications	12
3.4 Ranging, tracking, and timing applications	13
3.5 LISA and other space interferometry missions.....	14
3.6 Space qualification issues.....	15
3.7 ESA activities requiring stable lasers	15
4. Stable laser systems, trapped ion frequency standards and optical frequency metrology.....	16
4.1 Stable lasers.....	16
4.2 Trapped Ions	17
4.3 Trapped ions for microwave frequency standards	17
4.4 Trapped Ions for optical frequency standards	18
4.5 Optical frequency metrology and links from optical to the microwave.....	18
5. Discussions with third parties.....	20
6. Future stable laser requirements for space.....	21
6.1 Short term applications of stable lasers	21
6.2 Longer term applications of stable lasers	22
6.3 Workshops, clubs and international opportunities.....	22
6.4 Conclusion.....	23
Table 1 Examples of stability requirements for space applications of frequency standards and clocks	24
Table 2 Stable frequencies for space applications: Research efforts underway globally and future trends in development.....	25
Acronyms and symbols	26
REFERENCES.....	29
Appendix 1 Introduction to sources, local oscillators, frequency standards and clocks	36
A1.1 Distinction between various types of devices	36
A1.2 The past 40 years- atomic frequency standards and timescales	37
A1.3 Frequency- and time-related developments over the past 40 years.....	40
Appendix 2 Stability and accuracy issues.....	43
A2.1 Frequency stability and frequency accuracy	43
A2.2 Time stability and time accuracy	44
A2.3 Power laws of frequency and phase noise occurring on square-root Allan variance plots, and their sources in systems	45
A2.4 Impact of improvements in determining frequency and time information on user community applications over the years	46
A2.4.1 Impact on users of delivering frequency better over the years.....	46
A2.4.2 Impact of delivering time better over the years	48
Appendix 3 Frequency standards and microwave to optical intercomparison and frequency chain work	51

A3.1 Comparison of principles of sources, oscillators, frequency standards and clocks in the microwave and optical regions	51
A3.1.1 Oscillators.....	52
A3.1.2 Servos	52
A3.1.3 Reference resonances	52
A3.2 Microwave-to-optical intercomparison and frequency chain work.....	54
Appendix 4 Moving from the microwave to the optical	58
A4.1 Trends in applications technologies towards the use of higher frequencies over the past 40 years	58
A4.2 Frequency standards and measurement.....	58
A4.3 Ranging	59
A4.4 Use of absolute time in systems.....	60
A4.5 Trends in implementing optical technology: transitional development towards all-optical hierarchy.....	61
Appendix 5 Conference Paper: ULTRA-STABLE OPTICAL FREQUENCIES FOR SPACE*	63
Appendix 6 OHPs from final presentation at ESTEC	67
<u>ULTRA-STABLE OPTICAL FREQUENCIES FOR SPACE</u>	67

1. Introduction and the move from microwave to optical

Terrestrial telecommunications moved from the microwave to optical carriers for long-distance transmission with the advent of compact diode lasers and lightweight low-loss fibre: these optical systems offer much higher bandwidths (potentially up to 25 THz) and lower transmission costs. There are many reasons why optical communication systems are expected to supplement microwave-based systems for inter-satellite and other space applications. With much higher frequency (about 100,000 times greater) the optical, when compared to the microwave, has the potential for a commensurate increase in both frequency accuracy and bandwidth or information-carrying capability (see eg Bergquist 1996). Coupled with factors such as improved directionality for transmission - for example, the Voyager spacecraft mission to Saturn would have a beam over 2 million times more concentrated if it had used an optical system (Lesh and Rayman 1988), - lower equipment mass and dimensions, lower power consumption and higher detector efficiencies, with secure communication links, optical technology for space communications appears attractive.

In addition to communication requirements, there are other compelling arguments for developing ultra-stable optical frequency sources and detectors for use in space. At present, the microwave radiation is not only used for communication but also for navigation and tracking, and sometimes for scientific experiments collectively referred to as "radio science" (Lesh and Rayman 1988). As the switch from microwave to optical for communications proceeds, the component technology will find other uses in navigation, earth observation, inter-satellite synchronisation, and potentially for a whole gamut of aptly-termed "light-science" experiments. Although direct intensity modulation or "digital" (direct detection) has been used for early flight communication experiments and operational missions, coherent systems (and stable sources) may be required for the more demanding applications.

This study of ultra-stable optical clocks, frequency sources and standards for space applications was commissioned by ESA in late 1998. Following an oral paper at EFTF/IFCS in April 1999 an interim report was presented to ESA (see Appendix 5). It included OHP slides shown at the meeting and the text of a paper submitted to the proceedings of the conference. This final report expands on the material already provided and includes a significant collection of background material which is presented in appendices.

This introduction gives background information on optical developments, laser stability and linewidth issues. Following an examination of various potential space applications of stable optical frequencies in sections 2 and 3, section 4 highlights some of the laser-frequency control technology which will provide the next-generation of optical sources, frequency standards and ultimately even "optical clocks". Some of these devices may eventually be useful for space applications. Discussions with third parties are reviewed in section 5 and in section 6 we discuss a number of important short term and long term stable laser requirements for space.

1.1 Optical developments over the last few decades

There are several areas where there have been important optical developments over the last few decades. A few examples are given below:

(i) Industrial applications

- As mentioned above we note the impressive strides made in two decades with optical fibre communication, first at 1300nm and then at 1500nm. A chief engineer in the industry speaks of a "new paradigm" for telecommunications (Cochrane et al 1994). The ITU "ground rules" for frequency division multiplexing (FDM) are now in place (Knight 1996, ITU Telecommunications Standardization Sector 1995) and are already being exploited commercially, by e.g. CIENA in the USA, who offer up to 30 channels at 100 GHz spacing in the 1500nm (coherent communication) band - "providers are queuing up to buy and install" (Arie 1998). There is a great effort both in telecommunications R&D and manufacture, but also in instrument manufacture (optical spectrum analysers, etc.) to support it. Worldwide telecommunications is big business and likely to grow quickly, with video and pictures increasingly transmitted, e.g. via the Internet. Hence optical engineering in the near infrared and visible is rapidly expanding.
- High photon energy, e.g. from blue lasers is used in the printing industry.
- Ultra low-scatter optics and stable lasers have been developed for e.g. ring gyros for inertial navigation.
- A sizeable laser industry exists to supply markets in medicine, surveying and aligning, and cutting, machining or marking, optical data storage, and in science and engineering across a multitude of disciplines.

(ii) Military developments

There have been significant military developments demanding much greater use of optical hardware in systems such as:

- Display and guidance systems.
- Phased-array and frequency-agile radar, based on optical difference frequencies (Graydon 1998).
- Electromagnetic pulse-hardened command, control and communication systems.
- Free-space ranging.
- Inertial navigation.
- Earth orbit to ground data transfer.

(iii) Scientific research

In science, many of the most accurate experiments use optical technology, and the use of optics is rapidly increasing in areas such as:-

- Laboratory time & frequency and length standards, and metrology generally.
- Gravitational wave detection: two large experiments in Europe etc. (VIRGO, LIGO, Bender et al 1998, Gallop 1996).
- Practical distance and time-transfer measurements: ranging to the moon, to earth satellites, e.g. Lageos (Bears 1976), and the ESA LASSO time-transfer experiment (Veillet 1991) etc.
- Basic physics experiments to test relativity and gravitational theory (Will 1993), and quantum electrodynamics (QED) theory, the latter because of the computable atomic resonances of this region.
- Heterodyne generation of microwave signals and use of optical technology for e.g. phase shifting microwave signals - driven by the convenience of optical technology over microwave (Graydon 1998).
- Interest in nonlinear physics, such as at LENS (Laboratorio Europeo di Spettroscopia Non-lineari) in Florence. This is an example of a large-laser facility laboratory, to support university research in the EU. There are corresponding national laboratories such as the UK laser facility at the Rutherford Appleton Laboratory.
- Medical and dentistry, chemical, biochemical, physical and engineering applications requiring high photon energy light, e.g. blue light for processing photo-resist and other chemical reactions, near-IR and visible for eye surgery, short pulse lasers for biomolecular investigations, reaction kinetics experiments, and so on. In some cases stable frequency sources are used, e.g. to detect small Doppler shifts from identified-fluid motion in the body. "Optical tweezers" have been developed to manipulate molecules.
- High energy physics research, including research towards nuclear fusion carried out in several centres world-wide but involving laser breakdown plasmas at a large national facility at the University of Osaka, Japan, for example.

1.2 The impact of optical developments on space applications

There is much work successfully accomplished on programs in which optical frequencies have been or are being used in space applications. Consider the following subject areas:

(i) Communications

- The longest known range (6 million km) for laser transmission was demonstrated in December 1992 when Galileo Optical Experiment (GOPEX) optical transmissions were beamed to the Galileo spacecraft from the Table Mountain Observatory (Wilson et al 1993).
- High data rate links are needed, especially for space to ground, e.g. for photographic survey and earth resources satellites.
- Satellite to satellite links have been planned, e.g. the ESA SPOT-4 to ARTEMIS "SILEX" experiment (Lutz 1998). Commercial use however has not yet moved to the optical (Horkin et al 1998).
- Plans for high data rate links to/from Mars, see e.g. (Spence 1991).
- Similar plans for high data rates to Pluto (Mecherle et al. 1994) point to optical links.

- Optical transponders for long distance have been discussed (Degnan 1997).

Overall, the advantages in beam divergence angle, efficiency and weight point to optical systems for deep space, and the large data rates required (wide bandwidth) point to use of lasers between telecommunication satellites. However, active pointing systems are necessary as pointing jitter on typical (earth communications) spacecraft exceeds the optimal beam divergence for optical, though not rf, systems (Horkin et al 1998).

(ii) Ranging and Tracking

- When the Apollo mission put corner-cube reflectors on the moon, laser ranging, even with weak return signals, could establish the time of return to a few parts in about 10^{10} . This was a main pressure towards quickly revising the internationally-recommended speed of light from the results of ongoing laser measurements in 1973.
- Laser ranging experiments on close earth satellites such as Lageos (Bears 1976) and LASSO, the latter a trans-Atlantic time transfer ESA -funded experiment aimed at 100-200 ps accuracy (Veillet 1991).
- Distant optical ranging and tracking experiments have been carried out for decades, e.g. to the moon, see for example a report of the Second Conference on Instrumentation for Laser Tracking of Space Objects, Prague, 1975 listing 19 earth stations, most using rubidium or caesium frequency standards (Kokurin et al 1976). Also experiments to the planets and deep space are now in active preparation (Lesh 1998).

(iii) Science

- Fundamental experiments involving zero-gravity making use of the high resolution of F&T standards - such as in the recent flight of a laser-cooled caesium standard in zero gravity (Laurent et al 1998). Note that this was a good test of the diode lasers under flight conditions.
- For high resolution in the proposed gravitational wave detection experiment, LISA (discussed later in section 3.5), extremely high accuracy of locking a laser to the long-path interferometer is called for - although no explicit request for a local optical frequency standard as such appears in the proposal (Bender et al 1998).
- It has been suggested that accurate tracking of deep space craft might permit detection of gravitational waves, provided the ground station clock can be held to about 1 part in 10^{-17} over 10 -100s (Will 1993). A discovery of an apparent anomalous weak long-range acceleration of Pioneer 10/11, Galileo and Ulysses spacecraft has led the authors to call for optical tracking on the Pluto Express mission (Anderson et al 1998).
- A group of good frequency standards is planned to be on the space station (ACES), including two different hydrogen masers, for various experiments. Although none as yet are optical, the use of optical links is envisaged.

1.3 Stability, linewidth and accuracy issues

The Appendices gives background material on frequency sources, stability and accuracy issues in general. A laser's spectral density, is the most complete description of its frequency characteristics - it measures the spread of the energy in the Fourier frequency spectrum $S_x(f)$. A more commonly used quantity is $\sigma_y(\tau)$ the Allan variance, which can be derived from $S_x(f)$. The Allan variance gives a measure of frequency stability over a measurement interval characterised by τ (see appendix 2). Figure 1 gives examples of the Allan variance of a number of existing and potential microwave and optical sources and standards.

The linewidth of a laser is usually quoted over a timescale, generally significantly less than a second. For example the Lightwave 126 1064 nm NdYAG lasers has a specified linewidth of < 5 kHz over 1 msec. The relation of the linewidth to spectral density depends on the sources of phase noise present and assumptions about its bandwidth. Section A2.3 of appendix 2 briefly mentions the power law of the various phase noise contributions to the Allan variance.

There are few clear references in the space communications literature to laser linewidth requirements for sources, local oscillators and frequency standards. In 1993, at a prominent SPIE Conference on Free-Space Laser Communication Technologies (1993), when questioned on the issue of optical standards at a plenary meeting on relative merits of RF communications to Laser Communications, proceedings editor Stephen Mecherle responded with commentary over the choice of laser power, laser wavelength and method of communication (direct detection or coherent). There appeared to be no mention of laser linewidth, nor any mention of laser stability; these are critical issues which will be examined further in Sections 2 and 3.

One area where laser linewidth has been considered is in the context of the Deep-Space Network (DSN). Laser linewidth requirements for coherent communications was considered by Kazovsky 1985,1986a,b. Mecherle et al. 1994a,b using the Kazovsky results, clearly makes reference to a laser linewidth of 25 Hz for deep-space communication via a relay station for a Pluto Express mission. Such demanding requirements occur because of the low-data rate link which is limited by weak signal conditions.

System engineers may prefer communication links using direct detection (the use of pulses), which generally require less stable laser sources. Direct detection requires less complex receiver and transceiver hardware, is therefore easier to implement, and may explain why laser linewidth has not been widely discussed. But, as demand for bits-per-second has increased, fuelled by the development of reliable, relatively inexpensive, all-solid-state laser systems, so too has the demand placed on both microwave-orientated and direct-detection laser-orientated methodologies to meet these requirements. Preliminary work in the USA, Europe and Japan has resulted in test-bed missions such as GOLD and SILEX (1-50 Mbps capability) based on direct detection. In the late 1990s, attention has turned to the potential demands of multimedia services using satellite, and requirements of greater than Gbps transmission with, for example, SOLACOS (Europe) and OICETS (Japan). Coherent

fractional frequency stability (Allan variance) $[\sigma_y(2, \tau)]$

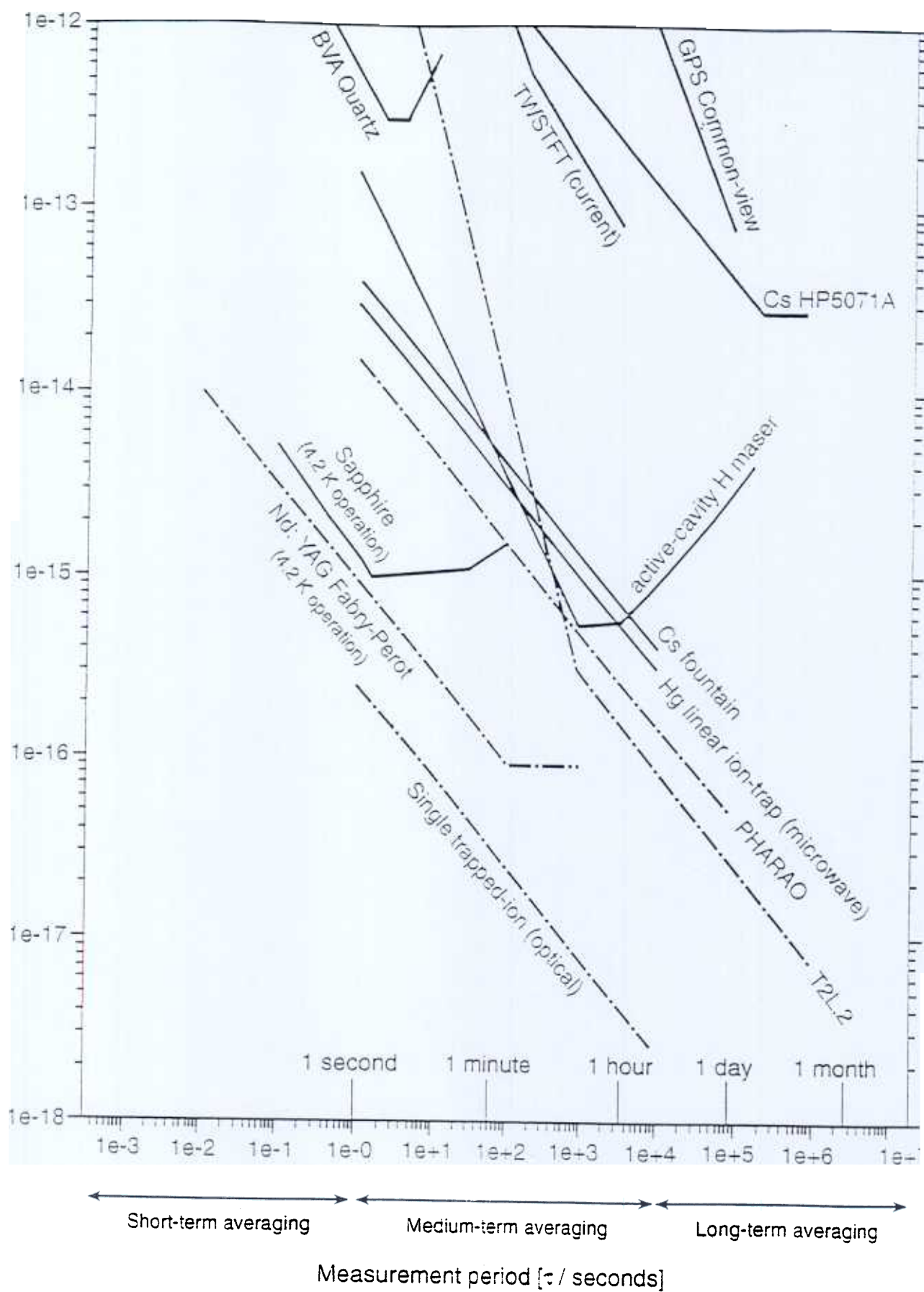


Figure Allan variance versus measurement period for frequency standards and time-transfer techniques

systems which are being seriously considered for commercial inter-satellite links may be far more demanding of laser source stability; they are discussed further in the next two sections.

2. Potential space applications of stable lasers

The move from microwave to optical frequencies has already been mentioned in section 1. Appendix 4 gives more background information on the move to the optical. Here we focus on three different areas which may eventually require stable lasers:

- communications
- navigation, tracking, and timing
- radio and “light” science

2.1 Communications

Reports on a variety of projects studying different aspects of space-based optical or laser communications which have been underway over the last two decades in Europe, Japan and the USA are reported in a special issue of Space Communications (CRL Workshop 1998) and in the annual proceedings of the SPIE Free-space Laser Communication Technologies workshops. The organisations interested in this field range widely from strongly commercial (e.g. driven by multimedia and Internet applications), to the military, to Deep-Space Network (DSN) users. Active project examples include:

- (i) The European Space Agency (ESA), SILEX (Semiconductor laser Intersatellite Link EXperiment) which will transmit 50 Mbps from LEO to GEO using direct detection (Oppenhauser 1991 and Tokler-Neilsen 1999);
- (ii) The US-Japanese “Ground-to-Orbit Lasercom Demonstration” (GOLD) - the first successful bi-directional optical communication with a satellite with rates of up to a Mbps (Wilson et al 1998), and;
- (iii) A programme funded by the US Ballistic Missile Defence Organisation will test intersatellite optical communication links (Biswas et al 1998).
- (iv) Terrestrial telecommunications are under increasing pressure to deliver the higher data rates following an explosion in demand due to the arrival of the internet in the late 1990’s. Satellite services may be able to compete with ground based systems in urban areas. In remote regions where it is costly to provide ground links, provision of services via satellite is seen as a solution. Alliances of major companies are being formed, with projected developments of constellations of up to 280 satellites. Initially, systems such as Iridium and GlobalStar with microwave mobile-satellite systems have evolved, but systems such as Teledesic employing optical intersatellite links for realising real-time Gbps data-rate transfer for “Internet-in-the-Sky”TM, appear to have undergone the definition phases (see www.teledesic.com).

In considering communications there are several different links to be considered between all of the following: the ground, satellites in low (LEO), medium (MEO) and geo-stationary (GEO) earth orbit. Intersatellite laser “cross links” are one of the options being seriously considered. Optical “uplinks” from the ground (see GOLD above), which may be blocked by cloud cover, are also being examined. One other disadvantage of optical systems is the requirement for very good pointing acquisition and tracking systems because laser beams diverge much less than microwaves. Much

work has been done on this subject, (see Lambert and Casey 1995 who also consider atmospheric effects on laser signals) but extensive discussion is beyond the scope of this report; it remains one of the most challenging research areas.

2.2 Navigation, tracking and timing

Tracking system frequency stability requirements for the Deep Space Network are currently 3×10^{-13} at 1000 seconds as described in Frequency and Timing Subsystem 1993-1997. DSN application examples might include: (i) satellite missions which pass close to the Sun, for the study of gravitational effects, and checking for variation in the fundamental constants (Hawking 1998); (ii) occultation-type experiments; or (iii) missions where precise one- or two-way Doppler tracking of the spacecraft signal is used. The Satellite Laser Ranging 2000 (SLR 2000) mission looks to develop high-bandwidth real-time communication links to Mars.

An example of time-transfer by laser-link (T2L2) is the MIR-based experiment which should make it possible to measure the performance of ground-based clocks having a relative stability of about 3×10^{-15} (Samain et al 1998) and for the ACES ensemble on-board the ISS against ground-based clocks using T2L2 (Fridelance et al 1997). An important advantage of optical over the microwave for ranging and time-transfer is the immunity to refractive index effects in the ionosphere and solar wind. Dispersion effects from the atmosphere are an active area of research, particularly through the GOLD programme using multi-frequency transmission with up to four carriers, to ameliorate scintillation effects. Anderson *et al.* recently reported an apparent anomalous weak long-range acceleration[11] from Galileo and Voyager satellite tracking data. They suggest that "the Pluto express mission could provide an excellent opportunity for high quality data from very deep-space, especially if optical tracking is used". The GNSS system requires very stable clocks for best performance. These may eventually be optical clocks, related to the microwave via highly accurate phase-locked links - see (Bergquist 1996) and section 4.5.

2.3 "Radio" and "Light" Science

A move to the optical for space-based communications opens up the vista of "light" rather than "radio" science experiments (Lesh et al 1998). The most stringent requirements for Deep Space Network (DSN) frequency source stability may be experiments which call for stabilities of 1.5×10^{-15} over 1000 to 3600 seconds for the Cassini mission (Dick and Wang 1998). A wealth of space-based scientific experiments may benefit from the use of ultra-stable laser sources and better clocks (Maleki 1997b). Two examples of research which would benefit from very well controlled optical frequency sources are given below:

A 'Pre-Phase A' Study has already been conducted into the feasibility of launching the Laser Interferometer in Space Antenna (LISA) platform (Bender et al 1998), as part of ESA's Horizon 2000 Programme. The LISA objective of detecting gravitational waves will test the laser and interferometer physics package to the limit (typical interferometer stability of 10^{-19} at 10^3 seconds averaging): mHz-wide space-qualified lasers are required (ESA Intended Invitation to Tender 98.1XA.07). A precursor to an

all-optical LISA system might be the development of optical hardware on the International Space Station (ISS): a first step to realising this goal is the ACES (Atomic Clock Ensemble in Space) which includes a laser link for accurate time- and frequency-transfer.

Very-Long Baseline Interferometry (VLBI) systems currently using microwave frequencies and microwave atomic frequency standards for synchronisation are limited by atmospheric propagation of the radiation through the ionosphere and the troposphere, and the ability to resolve the carrier phase. Two developments are currently taking place. The first proposes to operate an array of satellites in a new Space VLBI network - the Space Interferometry Mission (SIM), bringing better solid-angle resolution and atmosphere-free performance (Seidel and Dubovitsky 1999). The second proposal for next-generation European (or global) VLBI is to steer the network with optical signals, either terrestrially through optical fibres), or via a space link. Either way, ultra-stable optical sources rather than microwave frequency standards have an important role to play in the future to furthering our understanding of pulsars and for geodesy.

Optical frequency sources with stabilities that are potentially superior to microwave ones offer the possibility of realising more stable time standards. As can be seen from figure 1 at present the trapped Hg^+ 40.5 GHz microwave transition offers the best stabilities to a few thousand seconds. Microwave Hg^+ trap standards developed at JPL are being incorporated into the ensemble of clocks used at each of the ground stations for the deep space network (DSN). In the future single trapped ion based optical standards, which offer even higher stabilities, could be used to improve the stability of the timescale used for the DSN (see section 4.4).

2.4 Space applications of accurate frequency standards and clocks

Some examples of the stability requirements of frequency standards and clocks for various space applications is given in Table 1. It includes both optical and microwave examples and lists some of the published proposals using lasers. Table 1 also includes some time transfer examples which although laser based, do not at present demand very stable lasers.

Some published plans for MIR have not in fact taken place, amongst them, T2L2 ranging at 50ps accuracy (Samain and Fridelance 1997) and the space test of a hydrogen maser (Vessot et al. 1996). Both time-transfer systems are however still planned for the ISS (International Space Station), the former on the ESA ACES pallet (Feltham 1999) and the latter on a NASA pallet (Vessot et al.1999), both to fly about 2003. The Vessot time transfer system is microwave rather than optical.

One new development comprises the USA plan to fly a laser-cooled caesium standard under programs called PARCS - primary atomic reference clock in space - (Ashby et al.1999) and GLACES - glove-box laser-cooled atomic clock experiment - (Klipstein et al.1999) which is analogous to the European PHARAO apparatus included in ACES (Salomon et al.1999). The requirement for time transfer at the 1-2 parts in 10^{16} from the laser-cooled caesium clocks in space (to connect their performance to ground

observers/users) stretches both microwave (Vessot et al.1999, Ashby et al. 1999) and T2L2 techniques (Salomon et al.1999). The latter system for ACES has a target accuracy of 30ps for absolute comparison of time scales.

The prototype space cold atom clock (PHARAO) has a master diode laser with a 500kHz linewidth. Thus although this is a Cs microwave clock, it will need to have a well controlled space qualified laser system. (Laurent 1998, Salomon 1999, Lemonde 1999).

3. Optical Technology for space applications

Table 2 lists some of the research efforts underway or completed into stable frequencies for space applications. In this section we examine some of the technological requirements for stable optical sources for space applications

3.1 The move from micro-wave to the optical for communications

Growth in the demand for communication capacity has been highlighted in a number of reports and studies, with substantial revenues predicted. A 1998 International Technology Research Institute report: "Global Satellite Communications Technology and Systems" (http://itir.loyola.edu.satcom2/00_es.htm) gives the findings of a panel of US experts who visited many companies and organisations world-wide. As well as covering concerns about the weakening competitive situation of the US it points to rapid expansion of the satellite communications from a \$20 billion business in 1996 to a projected figure of \$75 billion in 2005. Internet access is seen as one of the drivers of this market. A recent article (Williamson 1999) explores this issue further, whilst expressing some caution about the commercial viability of the systems under consideration, faster Internet access via satellite is seen as an important objective. The report "Multimedia Satellite Investment Study" (Booz Allen & Hamilton 1997) examines the potential for satellite-based broadband multimedia services and predicts between \$14 and \$25 billion revenues for a European entrant by 2010. With such large projected revenues it is not surprising that at least 50 satellite systems have been proposed (DTT 1997).

As mentioned earlier in this report, there has been a desire to move to the optical for communications in space, the main driver being the potential increase in bandwidth or data rate (Chan 1987). This follows the terrestrial shift to the optical that accompanied the development of optical fibre. A number of the proposed satellite communication systems involve intersatellite links, these may well be best served by optical rather than microwave technology. Data rates in excess of 1Gbps are specified. The "Wideband inter-networking study" (WINS 1997) identifies potential configuration options for laser inter-satellite links. For example for a long range GEO-GEO link, a 1.5 μ m direct detection system was recommended. We have learned that at least one of the commercial systems presently under consideration (Teledesic) is a coherent optical system; this would require a narrow laser (see section 3.2).

Laser communications technology is also being considered for the next generation of NASA Deep-Space missions (Chen et al 1999). Both coherent and direct detection systems have been considered for deep space applications. The next sub-section addresses the issue of coherent versus direct detection which needs to be considered for optical applications.

3.2 Coherent and direct detection for laser communications in space

Whilst the SILEX and GOLD programs were based on direct detection, subsequent ground-based research and development of optical terminals in Europe has focused on coherent systems such as the Short Range Optical Intersatellite Link (SROIL) and Solid State Laser Communications in Space (SOLACOS) systems mentioned above (see CRL Workshop 1998). The issue of direct detection versus coherent (heterodyne or homodyne) systems for communications has been examined by several authors over the past 15 years (see for example, Saltz 1986, Czichy 1998). Coherent communication systems are far more demanding of laser stability and linewidth: examples will be given in the next section. There is no clear consensus on the best system to use, the choice depends on circumstances, the availability of lasers, detectors and the choice of coding scheme. Direct detection (DD) systems are certainly less complex and easier to use for demonstrators. However as mentioned above, at least one commercial system is pursuing the coherent option.

There are basic physical arguments as to why coherent communications based on frequency or phase modulation with a local oscillator at the receiver is fundamentally more efficient than a discrete amplitude (or polarisation) modulation system utilising direct detection. Two examples of references which give the argument are Lambert and Casey 1995 and Yamakawa et al 1999. In the case of direct detection the signal at the receiver depends on the *power of the transmitted laser beam*, whereas for coherent detection, it depends on the *square-root of the transmitted laser power*. Chan 1987 suggests that heterodyne systems offer 10-20 dB better receiver sensitivity than DD. One additional advantage of coherent detection is rejection of sun or other background light; the system has high immunity to background radiation.

It is beyond the scope of this report to consider the details of possible coding schemes, and the relative merits of homodyne and heterodyne coherent systems, but for example homodyne offers a 3 dB improvement in signal to noise over heterodyne (Lambert and Casey 1995). Czichy 1998 discusses the actual performance of various systems and compares them with theoretical expectations, asserting that incoherent systems have not achieved the predicted values. Figure 2 (taken from Czichy 1998) presents this data; the short range optical intersatellite link (SROIL) terminal uses a homodyne system and achieved better than 10 photons/bit sensitivity at a bit error rate (BER) of 10^{-6} .

3.3 Laser linewidth requirements for coherent communications

In situations where power is at a premium, where signal-to-noise is poor, or data rates are pushed to their limits (> 1 Gbps), coherent detection becomes attractive (Lambert and Casey 1995). For low-data-rate applications, where only low power levels can be achieved, coherent systems will require state-of-the-art optical frequency sources. For example, linewidths as narrow as 25 Hz have been mentioned for a deep space network (DSN) relay station application for the Pluto Express mission (Mecherle et al 1994a). Pulse position modulation techniques are currently being pursued for the DSN. These techniques offer 2.5 bit/photon rates (Lesh 1988), but need a laser which can be efficiently operated to emit pulses of power at irregular intervals.

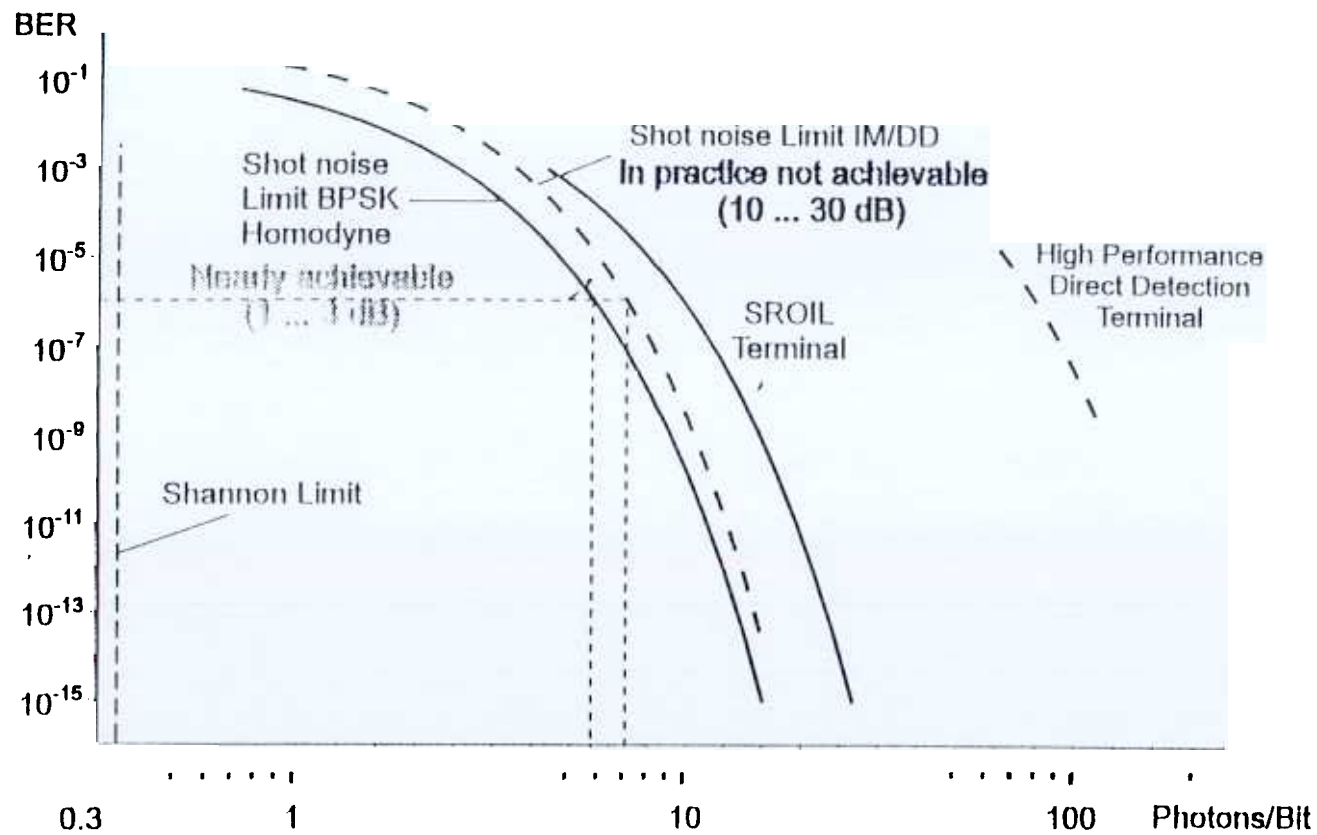


Figure 2 Theoretical sensitivity limits, bit error rate (BER) of coherent and incoherent optical communications systems compared with the practical achievable performance. Taken from Czichy 1998.

In a series of theoretical papers Kazovsky examines the laser linewidth required for various coherent communication coding arrangements (Kazovsky LG 1985, 1986a,b). Mecherle and Henderson 1991 use Kazovsky's results to compute the required laser linewidth as a function of R_b , the data bit rate, for different coding schemes. These range from $\Delta\nu = 2.02 \times 10^{-5} R_b$ for a homodyne binary phase shift keying (BPSK) scheme to $\Delta\nu = 2.34 \times 10^{-3} R_b$ for heterodyne BPSK. For a 1Gbps data rates these correspond to linewidths of 20 kHz and 2 MHz respectively. The homodyne value assumes 0.5dB carrier leakage which is needed for phase tracking. We have been unable to establish more exact specifications for the systems which are being developed for commercial purposes.

The coherent SROIL and SOLACOS systems both use Nd YAG lasers and have been the subject of extensive study and development (Pribil et al 1998 and Czichy 1998). Section 4.1 mentions how non-planar ring devices offer linewidths below 5 kHz. Space qualification tests have been carried out on these systems. One area that requires consideration is sensitivity to vibrations (Arnon and Kopeika 1997). Another subject which must be considered for intersatellite links is the maximum Doppler shift and maximum Doppler shift rates expected due to relative changes in satellite position. Chan 1987, estimates the maximum Doppler shift likely to be encountered to be ± 10 GHz with a maximum rate of shift of 13 MHz/s.

3.4 Ranging, tracking, and timing applications

There are a number of space application areas where it is not yet clear if optical frequency standards will be of interest. The Deep Space Network (DSN) currently has three ground stations with an ensemble of microwave clocks to provide frequency and timing signals. The DSN frequency and time subsystem stability requirements are specified for various applications (Deep Space Network, Frequency and Timing Subsystem 1993-97). Examples of some of the most demanding specifications include:

- Tracking, 3×10^{-13} for 1000 seconds to 12 hour intervals
- Radio Science, 1.5×10^{-15} for 1000 to 3600 seconds
- VLBI, 10^{-14} for 12 hour intervals

A frequency stability of 10^{-16} is being discussed for the Cassini mission to Mars (Dick et al 1998). The Hg^+ ion-trap based microwave standards mentioned in section 4.3 will soon be installed at each DSN ground station, to give improved frequency stability. One can only speculate on future DSN stability requirements but optical standards with very good stabilities may eventually be of interest, at present we are not aware of firm plans to investigate this option.

The accuracy with which position can be determined using the global positioning system (GPS) system currently depends on the stability of the satellite clocks used (Kaplan 1996). Without selective availability, which limits accuracy to about 30 m, the 1 sigma contribution from clock stability has been estimated to be 3 metres. This is another area worthy of further investigation; the long term possibility of improved stability using optical rather than microwave frequency standards should be reviewed.

3.5 LISA and other space interferometry missions

The Laser Interferometer in Space Antenna (LISA) project referred to in section 2.3 has a very demanding requirement for laser stability (Bender et al 1998). The project complements ground based gravity-wave projects in that it is aiming to detect low frequency gravitational waves with frequencies below a Hz using a space-based interferometer with arm lengths of one million km. The experiment would need to detect length changes of the order $\Delta l/l = 10^{-19}$ or less over timescales of up to 10,000 seconds. Achieving a laser stability to match this change is quoted as $6 \times 10^{-6} \text{ Hz}/\sqrt{\text{Hz}}$, which is orders of magnitude better than currently achievable using a single laser. A monolithic nonplanar ring Nd:YAG laser which has high intrinsic stability (see section 4.1) has been suggested for the LISA system. It is proposed to improve the stability of the laser by locking the laser to a temperature stabilised ULE cavity to give stability levels estimated to be $30 \text{ Hz}/\sqrt{\text{Hz}}$ at 1000 seconds. Further very significant reductions in laser frequency noise are required to meet the stability levels mentioned above.

Faller et al 1985, describe how by using two arms in the laser interferometer, the required laser stability for a gravity wave detector is reduced by the arm length to the arm length difference, $L_1/(L_1 - L_2)$, however the likely factor (typically 100) is not sufficient to meet the required laser stability. A laser frequency noise correction scheme has been proposed (Bender et al 1998) which will compare the mean phase of light returning from two adjacent arms of the interferometer to the phase of the transmitted light. A detailed analysis of this scheme suggests that it should be possible to make it reach the desired sensitivity, however it relies on knowledge of the difference in interferometer arm lengths to 200m.

Adding a frequency standard to LISA might permit (at low additional cost) an "alpha dot/alpha" experiment - to detect drift of the fine structure constant with time (Bekenstein 1982) - to be carried on board. Two clocks with mechanisms differently dependent on alpha are required (Turneare et al 1976).

A recent ESA intended invitation to tender IITT 98.1XA.07, calls for a high stability laser for space interferometry. It describes a Nd:YAG system with milliHz laser stability, which is a very demanding specification, although the time-scale is not given. As will be seen in the next section sub-Hz wide lasers with frequency stabilities of 3×10^{-16} at 3 seconds have been achieved (Young et al 1999). At JPL there is a project to build pre-flight test systems with Nd:YAG lasers locked to specially-mounted high-Q cavities for the Space Interferometry Mission (SIM) and DS-3missions (Seidel and Dubovitsky 1999). The fractional frequency stability requirement for SIM is $< 2 \times 10^{-12} / \sqrt{\text{Hz}}$, which has already been achieved with a prototype system.

3. 6 Space qualification issues

In general space applications require systems and components with low mass volume and power requirements. These issues need to be addressed for each optical application under consideration for example see section 3.3 which includes a number of examples of systems that have already been studied. Many of the basic building blocks are solid state and a number of components have been assessed for space qualification or flown already. A few points to consider which are worth highlighting include:

- The reliability of photomultiplier tubes (used for detecting low light levels) is a potential problem for systems with lifetimes of many years.
- The lifetime of laser diodes (which has been steadily increasing) may be a limitation in systems that need to run for 10 years.
- Vibrations of other instruments and equipment on a satellite may limit the stability and linewidth of stable laser systems which are very sensitive to vibrations, particularly at low frequencies. This issue has been addressed by Arnon and Kopeika 1997.

Further study is required to assess the suitability of the likely components for potential space applications of stable lasers and should form part of the considerations discussed in section 6.

3.7 ESA activities requiring stable lasers

ESA has had an optical communications programme for twenty years which has included several of the projects mentioned in section 2.1 and 3.2: e.g. SILEX and SROIL. Work such as the SOLOCAS program has also been funded by national agencies in Germany.

Over the last year or so, five intended invitations to tender (IITT) related to laser development have been issued by ESA which give a flavour of the interest in this field.

98.1CA.06 Long-range high-speed optical ISL terminals

(This project emphasised laser transmitters and receivers and has already been awarded)

99.1CA.01 High-speed optical networking in broadband satellite constellations

99.1XA.02 Optical ground station for optical data links and Deep Space missions

98.1XA.07 High stability laser for space interferometry

98.1XA.12 Core laser technology development

The first two IITTs listed relate to the ARTES (Advanced Research in Telecommunication systems) programme, which is driven by the high bandwidth requirements of multimedia services. The third aims to investigate ground to satellite links. The fourth IITT relates to the LISA programme and has been discussed in section 3.5. The last IITT is more general and will be discussed briefly in section 6.

4. Stable laser systems, trapped ion frequency standards and optical frequency metrology.

This section briefly covers recent developments in stable lasers, reviews the latest generation of standards based on trapped ions and mentions optical frequency metrology. These techniques may eventually be used in some of the space applications considered in this report.

4.1 Stable lasers

Figure 1 includes the projected Allan variance plots of some of the more stable laser sources and standards. Traditional wavelength or optical frequency standards based on lasers locked to gas cell standards have done little to narrow the laser linewidth. For example the 633 nm HeNe iodine stabilised laser has a stability of 5×10^{-12} at an averaging time of 10 seconds and a linewidth of below a MHz. Laser diodes typically have linewidths of 10's of MHz, but it is possible to reduce these to the sub-MHz using extended cavity arrangements.

Diode pumped NdYAG lasers have been constructed with a special "non-planar ring oscillator" (NPRO) geometry which have sub 10 kHz linewidths over 1msec (Kane & Byer 1985, Day 1990). The high stability of the device is achieved by the monolithic design of the NdYAG crystal which allows tight temperature control and has little sensitivity to acoustics. The Institute for Communications Technology of the German Aerospace Centre (DLR) has developed an "absolute frequency reference at 1064nm for coherent transmission and laser drift measurement" (Schulthess 1998). The doubled (green 532 nm) output is stabilised to the flank of a Doppler-broadened iodine absorption line to 7 MHz (2.5×10^{-8}). Whilst this stability is modest compared with the ultimate potential of Doppler-free and ion-trap-based optical standards currently being developed, it may be adequate for short-term requirements. It is important to look further ahead and consider the possibility of more demanding applications. Recently frequency stabilities (Allan Variance) of $< 10^{-12}$ between 1 and 100sec, have been achieved with iodine stabilised frequency doubled NdYAG NPRO systems (MacFarlane et al 1999, Hall et al 1999) using Doppler free techniques.

A new generation of optical frequency standards is emerging with ultra-narrow reference transitions for example two-photon transition in hydrogen and transitions in various trapped ions. To take full advantage of these narrow reference transitions, laser linewidths need to match them. This can be achieved using very stable high finesse reference cavities to narrow the laser and the best result published to date demonstrated a sub-Hz linewidth at NIST (Young et al 1999). This level of laser linewidth reduction in these so called "flywheel" lasers (or laser local oscillators) is achieved by isolating the reference cavities very well from vibrations and acoustical noise.

The sub-Hz linewidth NIST work used room temperature reference cavities made of ultra low expansion (ULE) material. This technique has been developed in several laboratories e.g. NIST, NRC, NPL and PTB. A high Finesse cavity (up to 200,000)

made with specially coated mirror substrates and a spacer of ULE is held in a temperature controlled evacuated housing. ULE materials do exhibit some creep, resulting in a drift of the laser; at NPL, drift rates of order 2.5kHz/day (a few Hz per minute) have been observed with such systems. Another cavity material which offers very high stability is sapphire at cryogenic temperatures. Using cryogenic optical resonators, a frequency instability of 0.7 Hz for integration times of 20 sec has been demonstrated (Seel et al 1997), however the linewidth over one second was 300 Hz.

At the UK National Physical Laboratory (NPL) there is currently a project aiming to stabilise the Nd:YAG NPRO lasers to ULE cavities which aims to achieve linewidths of one Hz or better. This research might well be of interest to the LISA project.

4.2 Trapped Ions

Microwave or optical transitions in ions stored in an ion trap are useful references for frequency standards for two reasons: (i) long interaction times are possible giving rise to narrow linewidths) and (ii) perturbations are low at the centre of the trap in the ultra-high vacuum conditions used (see Wineland et al 1993). Laser cooling can be used to cool ions and reduce Doppler effects considerably. The first-order Doppler shift is eliminated by confining ions in the Lamb-Dicke regime (Dicke, 1953), to a region less than the wavelength of the interrogating radiation. This can easily be achieved in the microwave region; it is more difficult in the optical case but can be achieved with good laser cooling. Various trap configurations are possible (Madej and Bernard 1999). In the Paul or rf trap an rf field is applied between a ring and two endcap hyperbolic electrodes, ions are trapped in a pseudopotential well, and a magnetic field is not used. The Penning trap combines a magnetic field with a static field between a ring and endcap electrodes to trap ions.

The frequency stability of an ion trap based standard in which measurement of the atomic states is limited by quantum noise, is given by the two sample Allan variance:

$$\sigma_y(\tau) = (\tau N T_R \omega_0^2)^{-1/2}$$

Here τ is the measurement time, T_R is time between two pulses (using the separated Ramsey field method) N is the number of ions and ω_0 is the frequency (Wineland et al 1989). For microwave based standards more than one ion is required to get a reasonable stability but at optical frequencies, one ion is enough to get the extremely good stabilities illustrated in figure 1.

4.3 Trapped ions for microwave frequency standards

Ground state transitions in a number of ions are suitable for ion trap based frequency standards. A recent review (Fisk, 1997) covers the status and detailed experimental arrangements used for several ions: $^{199}\text{Hg}^+$, $^{137}\text{Ba}^+$, $^9\text{Be}^+$, $^{171}\text{Yb}^+$ and $^{113}\text{Cd}^+$. Most of these systems have been studied using a linear RF trap which is a variant of the Paul trap, where there is a zero-field line rather than just a zero-field point as in the hyperbolic trap. For example a linear ion trap standard based on the Hg^+ 40.5 GHz transition will be one of the ensemble of microwave standards used to support the Deep Space Network (see section 3.4). These JPL systems have reported stabilities

$\sigma_y(\tau) = 5 \times 10^{-14}/\tau^{1/2}$ (Tjoelker et al, 1996). They are buffer gas cooled and uses a lamp to excite the resonance transition rather than a laser. A laser cooled Hg^+ 40.5 GHz linear RF trap standard is being developed at NIST; it has demonstrated a stability of $\sigma_y(\tau) = 3.3 \times 10^{-13}/\tau^{1/2}$ (over less than two hours) but with lower systematic uncertainty due to the second order Doppler effect (Berkland et al 1998). A Penning trap has been chosen for a laser cooled standard based on the 303 MHz transition in Be^+ because with a 0.82 Tesla magnetic field present the transition was independent of magnetic field to first order. Stabilities of $\sigma_y(\tau) = 3 \times 10^{-12}/\tau^{1/2}$ have been reported for Be^+ for $< 10^6$ sec (Tan et al 1995)

4.4 Trapped Ions for optical frequency standards

Very narrow optical reference transitions in a single laser cooled trapped ion may be used to stabilise a laser, this subject has recently been reviewed by Madej and Bernard 1999. One possible frequency reference is the quadrupole $^2S_{1/2} - ^2D_{5/2}$ transition in ions with an alkali-like term structure. The natural width of these transitions is in the region of 1 Hz. For example in $^{88}\text{Sr}^+$, the $^2S_{1/2} - ^2D_{5/2}$ “optical clock” transition at 674 nm has a natural width of ≈ 0.4 Hz. Other systems which are being considered as potential standards include alkali-like Hg^+ , Ca^+ , Ba^+ and Yb^+ , and the group III ions In^+ and Tl^+ . Together with Sr^+ these systems all lend themselves to the use of “shelving” (Dehmelt 1975). Figure 3 shows the generic term scheme for such a system. A fast resonance transition is used for laser cooling and fluorescence detection; when the narrow reference transition is excited, the fluorescence is extinguished. Observing these “quantum jumps” is a very sensitive way of monitoring the state of the ion and locking a laser to the reference transition.

In September 1997 the 674 nm transition in trapped Sr^+ was adopted at the *Comité consultatif pour la définition du mètre (CCDM)* as new recommended radiation for realising the metre (CCDM 1997). This was the first time that a trapped ion transition was chosen as a recommended radiation. At NPL the centre frequencies of the single $^{88}\text{Sr}^+$ ion 674 nm (445 THz) transition multiplets in two different traps was found agree to 3 parts in 10^{13} (Barwood 1999).

4.5 Optical frequency metrology and links from optical to the microwave

Appendix 3 section 3.2 discusses techniques for making optical frequency measurements and microwave-to-optical links. Such links would probably be essential for stable timing applications based on optical standards. Given scientific and industrial interest in more precise timescales, the contribution of an optical standard and an optical divider chain, could be desirable in a later version of ACES that might fly, say, after 2010. This would, like ACES, be aimed towards better time and frequency standards for all users, especially terrestrial ones.

All microwave-to-optical chains to date have involved quite large laboratory rooms, full of apparatus, with many kW of power demand and several hundred kg of mass - unsuitable for flight in space. However the first demonstration of all-optical frequency division to microwave, for a 1-THz optical difference frequency in the H 1S-2S

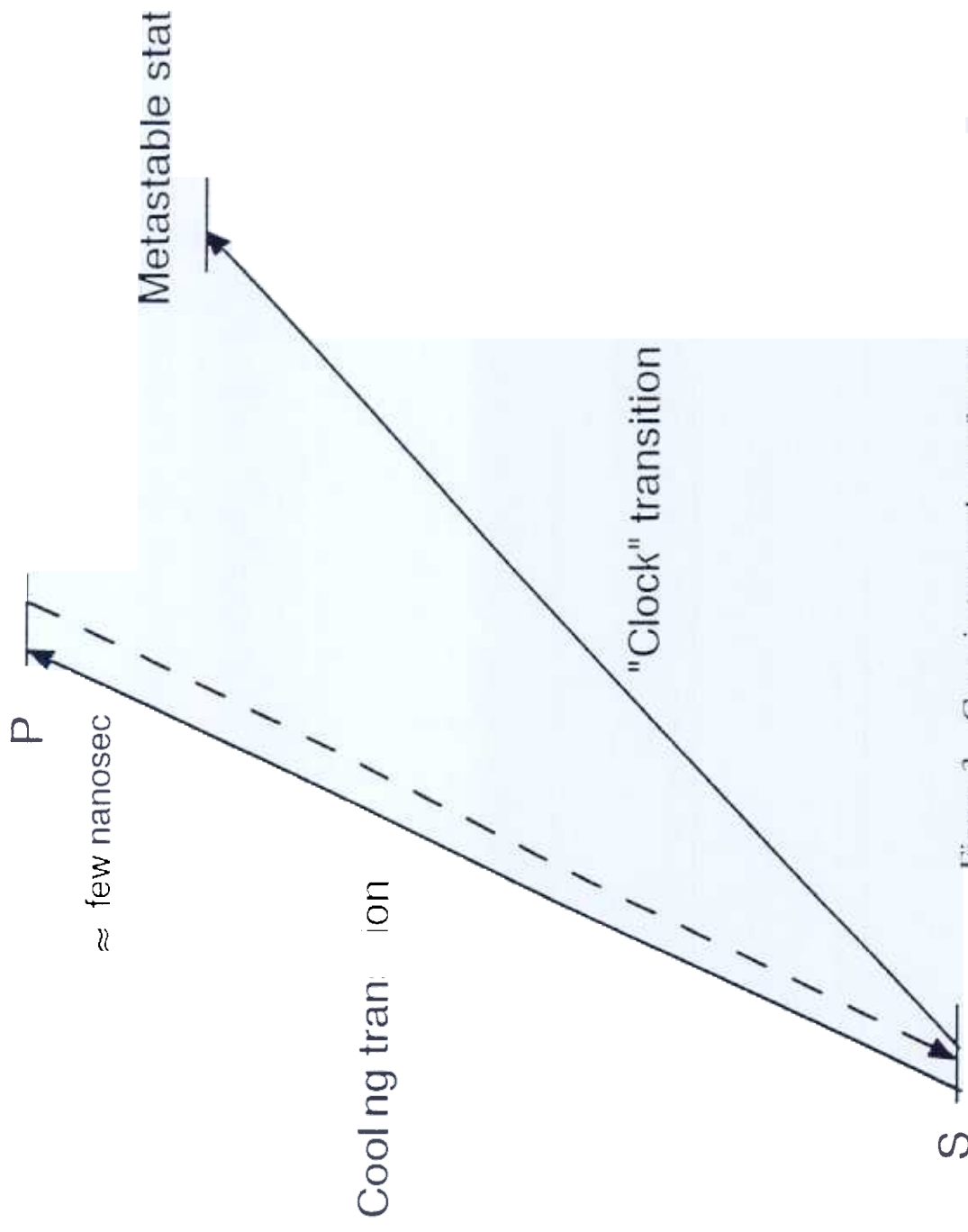


Figure 3 Generic term scheme for re- g at optical frequency I.
based a single laser-cooled pped (Dehr 197)

experiment (Udem et al 1999a) was achieved using all-diode-laser and all-solid-state frequency mixing.

Further, developments in the past year or so in Prof. T Hänsch's group in the Max-Planck Institut für Quantenoptik, Garching, include the measurement of an optical frequency difference of about 19THz (Udem et al. 1999a, 1999b) by directly comparing it with a wide "comb" of sidebands exactly spaced in frequency, generated by a Ti-sapphire femtosecond laser. This was a commercial system not specially developed for this new use. The method offers simplified frequency division down to the microwave region, and is about to spread widely in laboratories, judging from comments at EFTF/IFCS '99, but one should look to a timescale of 5-10 years for any system suitable for flight. Both the extended-cavity diode lasers used in the optical frequency divider schemes and the Ti-sapphire laser used as the femtosecond pulse generator require proving, although some similar diode lasers may have flown in PHARAO.

5. Discussions with third parties

As part of this study for ESA, a number of useful discussions took place with staff of organisations with various space related interests. These served to highlight the following issues:

- The rapidly changing alliances of companies interested in space based laser communication systems
- The diversity on approach to space based laser communication; some companies are only pursuing direct detection whereas others recognise the potential of coherent. Some organisations could not discuss details of their plans and requirements for commercial reasons
- The present laser specification for the LISA programme (as expressed in ESA's IITT) is recognised to be beyond the current state of the art.
- There has been little interaction between ESA and the US in this field of stable laser requirements, however the ESA laser communication program has involved collaboration with Japan.
- The knowledge gained from telecommunications work with Erbium doped amplifiers and laser diodes at 1.5 μm make this an attractive wavelength for coherent systems.
- The laser systems for coherent communications are not yet mature and experts are hesitant to define the requirements for frequency sources, stability and standards.

More generally these discussions with third parties were used to frame some of the observations presented in this report.

6. Future stable laser requirements for space

This report has examined a number of areas which might require stable lasers for space applications and reviewed recent stable laser developments. It is important to recognise that although there has been much thought given to the application of lasers in space, in practical terms the research field is in its infancy and offers significant opportunities for development.

Whilst gathering the material for this study it became clear that there is scope for exploiting the breadth of capability at ESA in the rapidly evolving field of space-based communications. There is a wealth of expertise in the microwave communication technologies which could have a useful input to make to the emerging area of optical communications if experts from the two fields could be brought together. The current structures in ESA do not immediately favour exploitation of the potential synergies in this area and a forum or co-ordinating mechanism should be established. Initially this could take the form of a series of meetings and workshops. Ultimately ESA should signal interest in developing the field of stable lasers in space by promoting suitable groupings of experts and subject areas within the organisation. The first steps have already occurred with IIT 98.1XA.12 “core laser technologies for space”.

Looking to the future it is worth highlighting various requirements over two timescales.

6.1 Short term applications of stable lasers

Two areas with the potential requirements in the next few years are as follows:

- **Coherent communications.**

The laser linewidths required for coherent communications depend on the coding schemes chosen and the data rate to be transmitted. In Kazovsky's papers, on heterodyne detection methods and homodyne detection methods, laser linewidth as a function of data rate and bit-error-rate is evaluated; homodyne detection wins out marginally. There is some difference in laser linewidth as a function of the coding methodology employed, but the general trend is that the laser linewidth is typically three orders of magnitude narrower (in Hz) than the bandwidth of the message broadcast (in bits-per-second).

Deep space optical communication systems may follow the pulse position modulation approach which does not require frequency stabilised lasers. Alternatively a coherent approach could be adopted (a study from 1994 suggested 25 Hz wide lasers would be needed for a mission to Pluto). The trade off between the two approaches for deep space needs further examination; the requirements for “space science” and navigation need to be taken into account. For example tracking requirements could demand 10^{-16} fractional stabilities to 1000 seconds.

For coherent systems which are now being considered commercially for intersatellite links, driven by multimedia/internet communications, linewidths of kHz to MHz will be needed. There has already been significant development work in this

area which should continue with space-based demonstrations. The requirement for absolute standards is less clear. Needs are probably best determined by those developing the systems, but at present partly for commercial reasons it may be difficult to establish their requirements. Iodine stabilised frequency-doubled Nd:YAG lasers provide an option which has already been demonstrated.

- **Gravitational wave detection.**

For gravitational wave detection (LISA) the ultimate stability of the lasers depends on ability to measure the interferometer arm lengths. The laser final stability (6×10^{-6} Hz/ $\sqrt{\text{Hz}}$) required to meet the desired sensitivity to gravitational waves, is well beyond what can be achieved at present. It would be useful to validate or demonstrate experimentally the scheme for laser frequency noise reduction proposed in the LISA pre-phase A report. The ESA IIT, 98.1XA.07 suggests investigating the capabilities of Nd:YAG lasers with mHz stabilities. This is an area worthy of further development as the desired laser specification is beyond that presently achievable.

6.2 Longer term applications of stable lasers

A potential longer term requirement which requires further study is:

- **High stability timescales related to Optical clocks.**

“Optical” clocks for improved time standards might be used, for example, as part of the deep space network or ultimately for an improved GPS system. The laser cooled ion trap based systems described in section 4.4 are a good choice for further study. As can be seen from figure 1, they offer the opportunity to improve the stability of timescales beyond those achievable using microwave standards. This would allow investigations and experiments needing very high stability to be carried out over shorter timescales.

6.3 Workshops, clubs and international opportunities

We suggest holding a workshop (of one or two days), sponsored by ESA, to bring together representatives of all parties in Europe with an interest in stable optical frequencies for space applications. This would be the first step in establishing how best to move forward and co-ordinate ESA’s strategy and activities in this field. One of the outcomes of such a workshop could be the formation of a “club” of organisations interested in stable laser sources and standards for space. Benefits to ESA would include spin-in of ideas through a central point of contact, newsletters and information updates via email.

The opportunities for testing laser sources presented by the international space station should be considered carefully. Narrow lasers are required for PHARAO (the ACES Cs clock project) which is already underway. A detailed analysis of potential laser based projects which could be proposed for later phases is needed. This would ideally take place as a joint exercise with the experts from around the globe.

There is scope for global collaboration in the field of stable lasers in space. Much of the existing work (both commercial and scientific) mentioned in this study is already global, involving players from Europe, North America and the Far East. There was

very significant US government funding of laser communication in space over the last two decades. There are likely to be strong benefits from building on the links between ESA and various US and Japanese organisations in this area. The international links between scientists and engineers could be further strengthened by the promotion of joint projects in the emerging field of optical frequencies for space.

6.4 Conclusion

Research in the area of optical sources, frequency standards and clocks is needed to establish the best choices for lasers and associated equipment for future space applications. The demands for optical technology are likely to be applications-driven, starting with narrow-linewidth lasers for commercial (and other) communications. The functions of navigation, tracking and “radio/light science” will push the stabilities and accuracies required from sources. The shift from all-microwave technology to a space-based scenario where optical technology augments microwave technology is already underway: the ultimate system could be all-optical, but that is likely to be a decade or two into the next millennium!

Table 1 Examples of stability requirements for space applications of frequency standards and clocks

date	stability	task	optical	operation notes	ref
Requirements for frequency standards and clocks					
'93	1.5×10^{-15} to 3600 sec	DSN ground segment	N		DSN93
'98.		weak anom.accel	Y	long range, spacecraft/Pluto	Anderson et al 98
'96	1×10^{-15} to few 1000 sec	SMEX, LITS clock	N	SMall EXplorer, relat. gravity	Maleki et al 1996
Past use of frequency standards and clocks					
'76	1×10^{-14}	H maser on rocket	N	gravitational red shift, relativity	Vessot 1980
'78 on	$<1 \times 10^{-12}$	GPS/ GLONASS	N	positioning, navigation, time	Daly et al 1992
'97	$2. \times 10^{-10}$ drift after 30 min.	Huygens probe	N	1-way Doppler tracking Cassini/Saturn	Kohl et al 1997
91	200ps	LASSO	Y	laser ranging from ground;micr.timing	Veillet 1991
97		cold Cs clock	(Y)	opt.pump+cool,micr. clock, flight test	Laurent 1998
Proposed use of lasers					
	See section 3.3	Commercial Opt. comm, LEO,GEO	Y	high data rate,0.5-5 Gb/s	Horkin 1998
		Coherent opt. Comm. Mars	Y	Mars Express 10-1000 Mb/s@2.5AU	Spence 1991
	2×10^{-12} linewidth	Coherent Opt. Comm. Pluto	Y	Pluto Express 670kb/s@40AU	Mecherle et al 1994
	1×10^{-16} over 1000 sec	Coher.com + Doppler Shift	Y	tracking	Chen & Win 1991
		LISA	Y	G-wave interferometer in space	Bender 1998
97on	10ps	ranging,T2L2,MIR	Y	space test of H maser	Vessot et al 96
99	50ps	ranging,T2L2, MIR	Y	LEO time transfer expt	Samain &Fridelance97
	30ps	ranging,T2L2, ISS	Y	time transfer for Atom.ClockExp.Space (ACES)	Walter 1998

Table 2 Stable frequencies for space applications: Research efforts underway globally and future trends in development

Project	lab	Description comment:	future aim	ref.
New generation with microwave reference				
PHARAO	LPTF/LKB/ CNES/LHA	laser-cooled Cs std. for space: uses sub-MHz wide laser diodes	better atomic clock	Laurent 1998 Salomon 1999 Lemondé 1999
LITS	JPL	40.5 GHz Hg ion trap $<10^{-15}$ @ 1000sec	DSN use	Prestage et al 1998
ACES	ESA	Atomic clock ensemble on ISS	Better performance	Walter 1998
Optical systems				
OCD/LTES	NASA/JPL	flight opt.com.demonstrator 780/840nm diode lasers Lasercom Test & Evaluation Station	kpbs to Mbps to planets; Gb to GEO	Lesh 1998
SILEX & LUCE	ESA & Japan	SPOT -4 to ARTEMIS and Laser-Utilizing Comms Equipt on OICETs. Also Canary Islands ground-station simulation of LEO 800-860nm laser diodes	LEO-GEO 50 Mbps	Lutz 1998
SOTT	ESA/Matra Marconi Space	Small Optical Telecom Terminal using MOPA laser diodes	GEO-GEO 1Gbps	Lutz 1997
SROIL	ESA/ Contraves Space	Short Range Optical Intersat. Links Nd:YAG coherent	1.5Gbps LEO-LEO	Czichy 1998
LISA	ESA	Nd YAG laser stabilisation	Gravity wave detection	Bender 1998
Mars comms.	NASA	Feasibility of comms at 10-1000 Mbps		Spence 1991
Pluto comms	NASA	Feasibility of comms at 670 kbps		Mecherle et al 1994
Optical systems: completed experiments 4				
GOPEX	NASA/JPL	ground to spacecraft link	completed	Wilson et al 1993
GOLD	NASA/JPL /CRL	ground to GEO orbit 95-6	completed	Wilson & Lesh97

Acronyms and symbols

ACES	Atomic Clock Ensemble onboard the International Space Station
ARTEMIS	Advanced Relay and Technology Mission Satellite (ESA)
BIPM	Le Bureau International des Poids et Mesures, Sèvres, France
BNSC	British National Space Centre
BPS	bit per second
BPSK	binary phase shift keying
BVA	Boite à Vieillessement Ameliore (crystal with improved ageing)
Cassini	spacecraft/orbiter, mission to Saturn & Titan (NASA/ESA, 1997)
CCDM	Le Comité Consultatif pour la Définition du Mètre
CCDS	Le Comité Consultatif pour la Définition de la Seconde
CGPM	La Conférence Générale des Poids et Mesures
CIENA	USA E coast company making 1500nm WDM/FDM hardware
CRL	Communications Research Laboratory, Japan
CSO	crygenic sapphire oscillator
DCF77	call sign of Mainflingen, Germany, 77.5 kHz std T&F broadcast
DSN	Deep Space Network (NASA/JPL)
DS-3	Deep Space-3 (NASA/JPL)
DWE	Doppler Wind Experiment, for Titan, on Cassini/Huygens
EFTF	European frequency and Time Forum (annual meeting)
EMF	electro-motive force
ESA	European Space Agency
ELF	extra-low frequency (~10-20 kHz)
FDM	frequency division multiplexing
FET	field effect transistor
FP	Fabry Perot resonator
Galileo	spacecraft to explore the moons of Jupiter (NASA/JPL)
GEO	geostationary earth orbit GEO600: German-British 600m laser-interferometric GW detector.
GLACE	Glove-box Laser-cooled Atomic Clock Experiment (NASA/JPL)
GLONASS	(Russian satellite positioning system, similar to GPS)

GOES	Geostationary Operational Environmental Satellite (USA)
GOLD	Ground to Orbit Lasercom Demonstration (JPL/CRL)
GO EX	Gallileo-Groarth to spacecraft) Optical Experiment (NASA)
G	Global Positioning System (NAVSTAR-GPS) (USA)
Huygens	descender Probe for Titan - Cassini/Huygens
IEN	Istituto Elettrotecnico Nazionale Galileo Ferrari - Torino Italy
IFC	International Frequency Control Symposium (annual) USA/IEEE
IR	infra red
JPL	Jet Propulsion Laboratory Pasadena, CA, USA Cal Tech./NASA
KTP	potassium titlphosphate crystal
LAGEOS	Laser Geodesy Satellite (NASA 1976)
LAER	light amplification by stimulated emission of radiation
LA: SO	LAser synchronisation from synchronous Orbit
LEN	Laboratori Europeo di Spettroscopia Non Lineare Florence Italy
LEO	low earth orbit Li ⁺ Ion Trap Standard
PTF	Laboratoire Primaire du Temps et des Frequences, Paris France
MASER	micro wave amplification by stimulated emission of radiation
Mars Express	proposed mission to Mars 2003 (ESA)
MJD	Modified Julian Day number
MS	(call sign of Rugby) UK 60 kHz standard T&F broadcast National Institute Standards and Technology (USA)
NPL	National Physical Laboratory Teddington, Middlesex UK National Research Council of Canada
OFCG	optical frequency comb generator
OFID	optical frequency interval divider (divide-by-2)
PARCS	Primary Atomic Reference Clock in Space (NASA/NIST)
PHARAO	Projet horloge atomique refroidissement d'atomes orbite France

Pi	0/	NASA/JPL space craft
Pluto	press	proposed mission to Pluto (NASA/JPL)
PTB		Physikalisch-Technische Bundesanstalt, German
PTFE		poly-tetra-fluoro-ethylene
QCO		quartz crystal oscillator
QED		Quantum electrodynamics
QW		surface
SDH		Synchronous Digital Hierarchy
SI		Le Système International d'Unités
SILEX		Semiconductor Laser Intersatellite Link Experiment ESA
SIM		Space Interferometry Mission (NASA/JPL)
SMEX		Small Explorer deep space probe proposal (NASA/JPL)
SONET		Synchronous Optical Network (USA)
SPOT-4		French earth observation satellite
ORIL		Short Range Optical Inter-satellite Link (ESA)
STS		Space Technology (NASA/JPL)
		International Atomic Time
TCXO		temperature-compensated crystal oscillator
TRANSIT		US Navy polar-orbital navigation satellite system
T&F		time and frequency
T2L2		transfer by light
ULYSSES		NASA/JPL spacecraft
USO		ultra-stable
USNO		US Naval Observatory Washington DC
UT		Universal Time (astronomical scale at deg, long.)
		Universal Coordinated Time (civil time-seconds offset from TAI)
TRGO		French-Italian laser interferometric GW detector
		very long baseline interferometry
VLF		very low frequency 30 kHz < ω < 300 kHz
WDM		wavelength division multiplexing
YAG		yttrium aluminium garnet
YIG		yttrium iron garnet

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Appendix 1 Introduction to sources, local oscillators, frequency standards and clocks

A1.1 Distinction between various types of devices

Ultrastable frequency sources are of interest for space applications, as well as for terrestrial use, across the whole electromagnetic spectrum, from RF through microwave, infrared and visible regions, and beyond.

Kinds of devices

For electromagnetic radiation sources there are various categories of interest:-

- (i) **Pure sources**, ie. spectrally narrow sources. These are typically oscillators of good "short-term" stability.
- (ii) **Local oscillators**, which are pure sources having emissions in the spectral region or at the frequency of interest and with good short- to medium-term stability, and which can be controlled or servoed in frequency. The term **local** in this context also has the subsidiary meaning of being at the point of observation, as in a heterodyne radio receiver.
- (iii) **Frequency standards** comprise a spectrally-narrow tunable source interrogating a reference resonance, usually in an atom, molecule or ion, together with a servo system to combine the short to medium term stability of the interrogating (local) oscillator with the "long-term" stability of the reference resonance.
- (iv) **"Clocks"** are derived from frequency standards capable of continuous long-term operation by attaching a frequency divider and pulse generator system to produce a train of pulses or markers equally spaced in time. Usually a 1-second pulse interval is used, for example for TAI (International Atomic Time) or UTC (Universal Coordinated Time). In general, when a frequency standard such as a caesium clock is set to generate a timescale, a device known as a phase microstepper is placed between the frequency standard and the divider chain to allow small adjustments of the time scale interval without altering the frequency standard itself. Certain kinds of frequency synthesiser with fine frequency control steps can be interposed for the same purpose, often in hydrogen masers.

A1.2 The past 40 years- atomic frequency standards and timescales

If we go back 40 years to 1959, we return to an era (Sarbachner 1959) without lasers, without micro-electronics, and only just with solid-state circuit devices, and to a time when the speed of light in vacuum was insufficiently well known for electromagnetic ranging or geodetic survey, even when limited by the fluctuations of the refractive index of the earth's atmosphere.

The previous decade had however seen the significant groundwork put in place for the present world frequency standard and timescale system, which is based upon atomic clocks rather than the preceding astronomical observations dependent upon earth rotation and earth orbit parameters.

The **caesium clock**, based upon separated-field observation of a ground-state magnetic dipole hyperfine transition in an atomic beam, devised by Ramsey (1950), had been put into practical use as a clock by Essen and Parry (1957), who together with the US Naval Observatory (USNO) had measured the frequency to be 9 192 631 770 cycles/second, (now Hz). The second for this measurement was derived from observations by lunar occultation camera at the USNO, and time intercomparisons were made by radio signals across the Atlantic Ocean, since the caesium clock was in Teddington, England, at the National Physical Laboratory. From the beginning, the accuracy of the caesium frequency standard was remarkable, about 1 part in 10^{12} , and commercial manufacture began very early, about 1955 (Steele 1992).

After this measurement the frequency of the caesium transition was adopted as the basis of the international definition of the second by the 13th Conférence Générale des Poids et Mesures (CGPM) in 1967 (BIPM 1985). A timescale, TAI, based on caesium clocks operating on the geoid was generated from 1958 and was formally recognised by the 14th CGPM in 1971. The arbitrary epoch of the scale was chosen so that TAI and the preceding timescale for astronomical time at the Greenwich meridian, Universal Time (UT), were coincident at 1958 January 1.

A second, practical, timescale was necessary, to keep within a fraction of a second of astronomical time for normal terrestrial purposes, including astronomy and astro navigation. Deviations greater than a second occur mainly because of irregularities in the rotation of the earth (Kovalevsky et al 1989). This timescale was termed UTC. For the first few years the frequency of the controlling caesium clocks was adjusted to make UTC differ appropriately from TAI, but finally a method of using whole second shifts (leap seconds) from the TAI scale was adopted. The time difference TAI-UTC was set at 10 s exactly at 0h on 1972 January 1, and the use of UTC was recommended by the 15th CGPM in 1975. The fluctuations in earth rotation have accumulated so that at 1999 January 1 the difference is 32 s.

Here we should also mention that the US Global Positioning System uses a caesium-based timescale, GPS Time, with a fixed (19-s) offset from TAI (the offset of UTC in 1980) but which does not introduce the leap second when UTC is changed. The difference of GPS and UTC is dealt with in software in order to display UTC-related time to users (Beard 1992, Allan et al 1997).

Whilst discussing clocks and the timescales they generate, it is useful to mention that timescales comprise a continuous flow of labelled time markers, as the second markers of TAI and UTC, with a specified starting point, as there is with the labelling of days in the Modified Julian Day (MJD) system in current use. Thus the definition of TAI with respect to UT and of UTC with respect to TAI is given above. Dissemination of absolute time in the UK has been discussed by Knight (1992). The broader matter of reference frames in astronomy and geophysics is discussed by Kovalesky et al (1989).

Other technology over 40 years: sources of narrow and stable frequencies

Quartz

The working electronic local frequency standard 40 years ago was the **quartz crystal oscillator**, typically running at frequencies between 100 kHz and 5 MHz when used as a frequency standard. This comprised an oscillator making use of a carefully cut piece of pure crystalline quartz - a piezoelectric material - in the feedback circuit, usually via electrodes evaporated onto the quartz. Usually the quartz crystal was sealed in a metal or glass can to protect from surface contaminants, which affect the mechanical (bulk mode) resonance frequency. Frequencies of quartz crystals tend to drift with age, settling down as they get older. This high -Q resonance gave an electrical impedance change on resonance to which the oscillator was locked. For use as an accurate standard within instruments such as electronic frequency counters (developed in the preceding decade) the quartz crystal is put in an insulated, temperature controlled oven, possibly also with vibration isolation. Accuracies sometimes exceeded 1 part in 10^9 over a period of a few months could be obtained with selected "ovened" oscillators provided the ovens were always on, but non-ovened ones were typically no better than about 1 part in 10^6 . Because of the wide use of quartz crystal oscillators, and later, of delay lines, there was considerable production and scientific research.

Over the 40 years, with the development of cheap micro-electronics, the emphasis in engineering has moved to using fewer but better quartz crystal oscillators, e.g. not one per channel but one per instrument, the channel frequencies being generated by synthesiser. For domestic and personal use, however, cheap quartz oscillators provide timekeeping within a few seconds, and quartz oscillators have become ubiquitous in microcomputers and controllers for domestic electrical equipment. At the other extreme, specialised research, such as at Besançon (Besson 1977) has produced extremely low-noise and frequency-stable quartz crystal oscillators, such as the BVA (Boite à Viellissement Ameliore; translated: "box with improved aging") used as a frequency standard in synchronous telephone networks and as a low phase-noise reference in synthesis chains for use in other frequency standards such as caesium clocks. This oscillator uses electrodes that do not touch the vibrating piece of quartz. It should be noted that, before atomic frequency standards were introduced, the best maintained laboratory standards were quartz ring (Essen) resonators, or quartz bar standards (General Radio Primary Frequency Standard Type 1100-AP see (Sarbacher 1959)), so that quartz-controlled oscillators have a long and distinguished history.

Masers: ammonia and atomic hydrogen

An early "quantum" frequency standard was the molecular ammonia maser operating at 23 870 MHz. "Maser" is an acronym for "microwave amplification by stimulated emission of radiation", and "laser" is the equivalent for light amplification. The ammonia maser was investigated as a frequency standard at the National Bureau of Standards, Boulder, Colorado, USA, (Lyons 1950) but was in a few years superseded by other devices.

Hydrogen maser

The most significant maser development as a frequency standard was the atomic hydrogen maser, operating at the relatively low frequency of 1420 MHz (Goldenberg et al 1960). The maser unlike the Cs beam standard could operate either in passive form or as an emitter of radiation. In the latter form it is much more stable than caesium clocks in the short to medium term, over periods of 1-10 days. The best ones can hold frequency to about 1 part in 10^{15} over that time. However, for the definition of the second the Cs standard was adopted, and not the maser. This was partly because the H maser was developed later, and partly because of a difficulty with the hydrogen maser arising from confinement of the state-selected atoms in a bulb inside a microwave cavity. During emission of a microwave photon the atoms makes many bounces off the bulb wall, and a "wall shift" is introduced into the frequency of the emitting transition. PTFE coatings are used on the inside of the (quartz) bulb to make the collisions more elastic, but it has proved difficult to ensure that masers operate at the same absolute frequency, owing to the variability of the wall shift, maser to maser. However the storage time is about 1s, offering a high spectral line Q of 1 part in 10^9 , which contributes to the excellent short- and medium-term behaviour. The maser, because of the long interrogating wavelength, is rather bigger and more massive than commercial versions of the caesium clock. Smaller, portable versions have been designed using e.g. dielectric-loaded cavities to reduce the size. Such cavities, also with a smaller bulb, have lower Q and do not always sustain maser oscillation, so that the portable versions often act as passive standards. H masers have flown in space, as, for example, the on-board clocks in the satellites of the Russian GLONASS navigation system (Daly et al 1992).

Rubidium standard

Another quantum standard is the rubidium standard operating near 6835 MHz. In practice this can be small and compact device, but it is less accurate than either the Cs standard or the H maser. It differs in that it uses optical pumping of the atom inside the microwave interrogation cavity. Light from an ^{87}Rb lamp illuminates ^{87}Rb atoms in the microwave cavity via an ^{85}Rb gas cell acting as a filter, so as to pump out atoms from the lower of the two microwave-separated levels only. If the microwave signal is tuned to the transition frequency, it equalises the populations of the two levels, and the ^{87}Rb light is absorbed again. Detection of this absorption is used to servo the microwave oscillator to the reference transition (Bender et al 1958). As with the H maser, the Rb atoms need to be confined. Here a buffer gas is used, which is a source of collision-induced frequency shifts from the unperturbed state. Rubidium standards are widely used at the 1 part in 10^{10} level of accuracy as local (secondary) standards. A notable

commercial development was the introduction about 1970 by Efratom (Jechart 1973) in Germany of a compact device enclosed in a 100-mm cube, also at lower cost than before. Because the Rb atom is pumped in situ in the microwave cavity, there is not the problem of "using up" the supply of the atoms, as there is with the caesium beam and H maser, where prepared and state-selected atoms are continuously injected, used, and then lost. Thus the Rb standard is suited to continuous use for long periods. However, the technologies of the caesium and hydrogen standards now permit operation for periods of 10 years or so, more for hydrogen, quite comparable with the life of rubidium standards.

Lasers

About 1960 laser action was discovered, in both solid media and in gases, the latter having discrete narrow emission lines well suited to metrology. Within a decade suitable gas laser lines were locked to absorptions in gases that coincided in frequency with the lasers. A saturated-absorption technique was evolved, in which molecules in low-pressure gas cells were interrogated by light waves travelling in opposite directions. This selected only the transversely moving molecules, and so eliminated the first order Doppler effect. By about 1970 the red He-Ne laser at 633 nm, 474 THz, was locked to an absorption in I₂ (Hanes et al 1969) and was in wide use as a secondary standard for length measurement. Also another He-Ne emission at 3.39 μ m, 88 THz, had been very accurately locked to an absorption in methane (Barger et al 1969). In addition, the numerous CO₂ laser lines in the 9-10 μ m, 30-THz, region could be locked to the same line in CO₂ by observing a saturated absorption feature in the induced 4.3 μ m radiation from an external gas cell. The stabilised red He-Ne and CO₂ lasers had initial accuracy of about 1 part in 10¹⁰, but the methane-stabilised laser was better, at about 1 part in 10¹¹. A development of this laser, in which the three hyperfine components of the methane absorption are resolved, is more accurate again, and has been used to transfer frequency measurement from one laboratory to another in an experiment reaching a final accuracy of 3 parts in 10¹³ (Udem et al 1997). In another experiment this stabilised laser was also operated quasi-continuously as a clock for about 10 days as a laboratory demonstration. For this a frequency synthesis "chain" from the microwave region was used at the lower end to generate a train of 1-s pulses derived from the laser frequency (Bagaev et al 1983, Weiss et al 1988). It should be noted that to divide an optical frequency to obtain 1-s time markers is more difficult than dividing a microwave frequency, making optical clocks mainly a matter for the future - see Appendix 3.

A1.3 Frequency- and time-related developments over the past 40 years

Speed of light measurement with lasers

An important historical development with lasers was the exact measurement of the speed of light, to the full accuracy of the ⁸⁶Kr lamp emission line wavelength in the orange used formerly to define the metre. The method was to measure both the frequency f against the caesium standard and the wavelength in vacuum λ_0 against the krypton standard of a stabilised laser, to obtain the speed of light in vacuum as the product, $c_0 = f \cdot \lambda_0$. Frequency measurement was extended to the CO₂ stabilised lasers

near 30 THz, and then to the methane stabilised laser at 88 THz, 3.39 μm . At this point in 1973 a new value of the speed of light was recommended by the Consultative Committee on the Definition of the Metre (CCDM 1973) to be $299\,792\,458 \pm 1.2$ m/s, two orders of magnitude more precise than before. This was immediately useful to convert time of flight measurements of light pulses reflected from the moon to distance. A decade later, when laser frequency measurement had been extended to the stabilised lasers in the visible region used for laboratory length measurement, the definition of the metre was changed. The metre was defined broadly as that distance that light travels in vacuum in $(1/299\,792\,458)$ s, so that the speed of light became a fixed constant, and length was defined by reference to the standard of frequency (BIPM 1984). This definition allows equal accuracy to be obtained for length measurement: (i) by time of flight measurements, as used in space, and (ii) by interferometric measurements used in the laboratory.

This process parallels other developments in the subject of Quantum Metrology, in which accurate measurements of the fundamental constants have been used to refer other units to the standard of time and frequency, because the latter is more accurate than any other measurement standard, and measurements against it have higher resolution. Another instance is the reference of the unit of EMF, the volt, via precise observations of the Josephson effect to achieve accurate measurement of h/e , where h is Planck's constant and e is the charge on the electron (Taylor et al 1989).

Laser pumping and cooling

It is worth noting also the developments in the past two decades in the use of lasers to pump and cool atoms. For example, rubidium clocks pumped by lasers rather than lamps have been experimented on, and the whole new subject of laser cooling of atoms, molecules and ions (Phillips 1984) has had profound effects. The need is always to minimise the relative motion in the laboratory frame of the system under interrogation, to avoid the frequency-shifting Doppler effects. Also, reduced motion allows longer interrogation times and thus reduced frequency linewidths.

The recently developed laser-cooled caesium fountain clock (Clairon et al 1996) and its space-flight equivalent, PHARAO (Laurent et al 1998, Lemonade 1999, Salomon 1999) depend upon accurately controlled lasers and have accuracies of order 1 part in 10^{15} .

Measurement of the Rydberg constant with lasers

One method of measuring the Rydberg constant is to make accurate frequency measurements on electronic transitions of simple atomic systems, such as hydrogen or helium. The precision of such experiments, often carried out on beams using two-photon techniques, at one time exceeded the accuracy available from the iodine stabilised visible lasers (Zhao et al 1986), and recent research has fully exploited the accuracy of the best mid-infrared stabilised lasers, including the methane stabilised laser. This work culminates in the recent measurement in Germany (Udem et al 1997) of the hydrogen 1s-2s transition in the ultraviolet to 3 parts in 10^{13} , and in France (Beauvoir et al 1997) of other transitions of comparable accuracy. The drive towards higher accuracies in such experiments comes from their use to compare theoretical

calculations of the transition frequencies with the observations, and so test quantum electrodynamic theory and understanding of the physics.

Appendix 2 Stability and accuracy issues

A2.1 Frequency stability and frequency accuracy

Where accurate frequency standards and the time scales derived from them are concerned, four major parameters are the frequency stability, frequency accuracy, time stability and time accuracy.

The **frequency stability** of a single oscillator, free running or stabilised by a servo to a reference, is conveniently described by its rms fractional frequency deviation as a function of the averaging time of the observation. This is usually obtained by taking the square root of the Allan two-sample variance of the fractional frequency, σ_y^2 where $y = \Delta f/f$. The Allan variance (Barnes et al 1971) is a two-sample variance of a set of N successive measurements taken on the oscillator, with the oscillator running continuously, with an averaging time, τ . The rms of the differences of successive count pairs taken with a counter with gate time τ , the total number of such pairs N being typically 100 or more. The resulting values of $\sigma_y(2, \tau)$, being a statistical measure, has uncertainty depending on $1/\sqrt{N}$, which is small if $N > 100$. This two-sample variance is used because it does not "blow up" if the oscillator has straight-line frequency drift, as a variance of the whole measurement set would do. The bandwidth of the measuring system, f_h , can affect the result, see below.

For small values of τ up to about 0.1 s, σ_y decreases and then encounters a "flat" region up to a few s or more, called the **flicker floor**, before then rising again as a result of drift or random walk of frequency. The best stability of the oscillator is that achieved at the flicker floor. A shorthand definition of "short-term" stability is that for values of averaging time τ up to the start of the flicker floor. "Medium term" might refer to times over which the flicker floor is held, and "long term" to times beyond the flicker floor, out to say 10^5 s (1 day) or to $\sim 10^7$ s (1 year). However, depending on the context, with frequency standards, "long-term" might be used to refer to years, "medium term" to say 10 days, and "short term" to perhaps minutes.

The term **frequency accuracy** can really only be applied to stabilised oscillators, which are servoed to some reference to suppress the drift. Such a reference might be a mode of a quartz crystal or a molecular or atomic resonance. An ideal frequency standard should comprise a perfectly tunable oscillator servoed by a noise-free circuit to an unperturbed reference resonance. Frequency accuracy is a measure of how close the oscillator keeps to the frequency of the **unperturbed** reference resonance. One assumes that the unperturbed reference resonance in e.g. an atom, molecule or ion has a unique absolute value without error in the unperturbed state. Where there is some "fixed" perturbation such as from g acting on the Cs resonance used to define the second, the value is specified: in this case the clocks are to be on the geoid.

To test the frequency stability of two similar oscillators, they can be heterodyned and a difference frequency produced which is in the range of a counting system used to determine the square-root Allan variance. Usually a plot is made of $\log(\sigma_y)$ against $\log \tau$.

Then considering equal contributions from each oscillator at all points, σ_y is divided by $\sqrt{2}$ to obtain that for a single oscillator.

A2.2 Time stability and time accuracy

A time scale can be imagined to be created by dividing down the frequency of the reference stabilised oscillator to give a 1-Hz sine wave, which is then turned into a narrow pulse at 1-s intervals. To compare time scales the time differences between corresponding 1-s pulses are usually observed.

The square-root Allan variance can be obtained for time quantities as for frequency quantities, to give a σ_x where $x = \Delta T/T$, T being the period, analogous to σ_y for f .

If f is the oscillator frequency, the phase ϕ corresponds to the flow of time:

$$2\pi f = d\phi/dt, \text{ so } \phi = 2\pi \int f \cdot dt + \text{const.} \quad \text{Eq.1.2.1}$$

If the frequency has an offset Δf from nominal, f_0 , the offset ΔT in its period T will be such that $\Delta T/T = -\Delta f/f$. If Δf is positive the clock will run "fast" and is said to have a "rate" higher than normal. The accumulated phase of the clock will differ from the nominal, ϕ_0 , as

$$\phi - \phi_0 = 2\pi \int (f - f_0) dt \quad \text{Eq.1.2.2}$$

For a fixed frequency offset, the timescale error accumulates proportional to the time run. For a frequency with linear drift in time, as for a hydrogen maser, the timescale error is parabolic. If the frequency drifts through zero from a given offset to the offset of the opposite sign, the time offset will return to that at the starting time.

Time stability is a measure of how much the second markers deviate from the norm as the time scale runs and can be portrayed by σ_x . However, looking at Eqs.1.2.1 and 1.2.2, **time accuracy** is composed of two things, (i) the "const." at which the clock was initially set to the nominal timescale, such as UTC, and (ii) the accumulated marker offset arising from rate offsets and fluctuations. The truth of this is confirmed simply by thinking of the accuracy of a domestic wind-up alarm clock next morning.

In practice, strangely enough, a "**good**" clock is one simply with a stable and predictable "rate" or frequency. If the setting error at a given time is known, and the rate offset is known then the time error can be calculated as a function of time and the correction applied to the readout, even in real time. A stable and predictable rate is above all, valued, and this is the same as **frequency stability**. Such a clock is necessarily operating as a **secondary standard**. For a **primary standard of time**, i.e. to realise time from the definition of the second, **frequency accuracy** is required above all, since by definition the clock has to have a self-correct average rate. The timescale can still be inaccurate, depending on how well it was set to the previously-running timescale after it was started.

Given that clocks can stop and go wrong, the value of a particular clock depends on how often and how accurately its time is checked against that of other comparable clocks. There is a philosophical uniqueness about **time as a dimension**. All that is known about a clock is in the past, up to the present. Extrapolation to the future has to be a prediction based on what is known. Its data is not available to adjust or smooth present timescale data until long afterwards. There is thus **retrospect** in estimating a clock's relation to accurate timescales such as TAI or UTC. In widely separated national laboratories UTC is realised by nominated clocks, giving the national timescales. When all the data for comparison of contributing clocks is collected, typically every month, the average timescale UTC is calculated. The offsets of national timescales such as UTC (NPL) from UTC are published for MJDs ending in a "4" and "9" at five day intervals in BIPM's Circular "T" (BIPM 1992). Time is thus known better in retrospect than in "real time".

Practical clocks running timescales in the national laboratories are called upon since 1990 not to deviate from UTC by more than 1 microsecond at any time. Fortunately the clocks in different laboratories are intercompared many times a day, and calculations are possible once a week, via the GPS common-view schedules arranged by BIPM. Allowing a safety margin, if the maximum rate error allows a clock to deviate by 100ns in 40 days, this is 2.5ns/day, implying the average $\Delta f/f < 2.5 \cdot 10^{-9}/10^5$, $\sim < 2.5 \times 10^{-14}$. A hydrogen maser with $\Delta f/f$ drifting at 10^{-15} /day can be used to achieve this, but it is difficult to achieve with even the best commercial caesium clocks.

A2.3 Power laws of frequency and phase noise occurring on square-root Allan variance plots, and their sources in systems

A typical log σ_y vs log τ plot has approximately straight elements, starting from small averaging times, of slopes successively of -1, -0.5, 0 and +0.5 or +1, see Figure A1. The kinds of random noise associated with these slopes, which dominate the frequency source's performance at the different regions of τ are:

<u>slope of σ_y</u>	<u>type of noise</u>
-1	white phase or flicker phase*
-0.5	white frequency or random walk phase
0	flicker frequency
+0.5	random walk frequency
+1	linear drift of frequency

* Because of the ambiguity of the root-Allan-Variance plot to these quantities, a "modified Allan Variance" has been introduced, by which they can be separated, if needed (Allan et al 1981). The quantities can also be separated by varying the filter bandwidth under which the data is taken (Audoin et al 1976), since they respond differently to bandwidth. A recent review of the characterisation of frequency stability in precision frequency sources has been given by Rutman and Walls (1991] covering such issues.

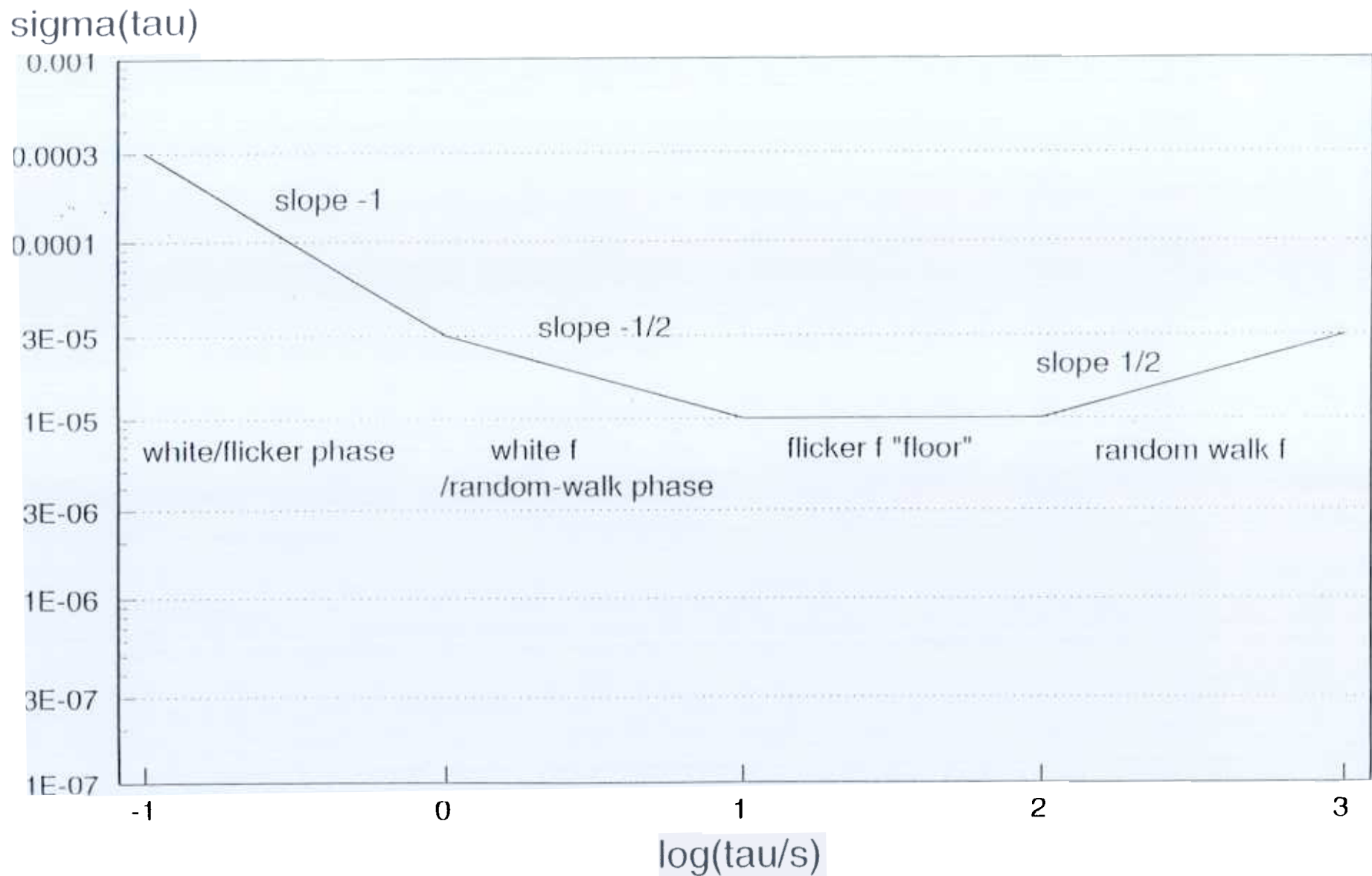


Figure A1 Schematic Allan variance plot $\sigma_y(\tau)$ against τ , showing the different noise slopes described in the text

Oscillators such as quartz crystal oscillators and active hydrogen masers have short term noise with slope (-1) since they utilise true phase lock loops. Others where a system is passively interrogated, such as Rb and Cs standards, have instead frequency lock loops and the short-term noise decreases at slope (-0.5) (Hellwig 1976). The stability reached by the **flicker floor** is largely determined by the "Q" of the reference resonance. The higher the Q, the better the ultimate stability (Hellwig 1984).

A2.4 Impact of improvements in determining frequency and time information on user community applications over the years

In considering the impact on users of the advances in delivery of frequency and time over the years, we start by considering frequency. There is an overlap with time because better frequency standards (standards of time interval) underpin the delivery of better absolute time. However, as will be seen, the widespread use of absolute time references is much later than the use of absolute frequency standards and depends on developments such as redefinition of the metre and provision of accurate auto-ranging as a function of time, as occurs with the GPS system.

A2.4.1 Impact on users of delivering frequency better over the years

We start our consideration with the introduction of atomic frequency standards, particularly the caesium beam standard, the hydrogen maser and the rubidium gas cell standard (Audoin 1976). The better dissemination has mainly resulted from the continual improvement of such standards, and of quartz oscillators, as well as on developments such as cheap microelectronics.

Notable commercial frequency standard developments were the manufacture of portable caesium standards with high stability (long tube) options, by e.g. Hewlett Packard, starting in 1964 (Model 5060A), replaced from 1968 by the 5061A/B until 1991, when a redesigned version with four times the former stability (Model 5071A Opt.001) became available. The improved stability was in part from the use of servos to counter environmental changes. A miniaturised and cheaper rubidium gas-cell standard in a 100-mm cube was produced by Efratom in Germany and the USA, from about 1973 (Jechart 1973). Other manufacturers later followed this approach. Hydrogen masers remained expensive research devices until quite late, about 1988, but now see substantial commercial production by such companies as Sigma-Tau Corporation in the USA and Kvarz in Russia, and by the Observatoire de Neuchâtel. Whilst typically 4 or 5 times the cost of a caesium standard, the maser is now widely used, both to support UTC timescales in national laboratories, and for Very Long Baseline Interferometry (VLBI) because out to ten days or so, it can hold frequency with drifts of order 1 part in 10^{-15} per day, two orders better than a caesium standard. It also serves as a local oscillator for experiments towards new standards using laser-cooled ions or atoms, for which the Q of e.g. "forbidden" transitions can be extremely high and the interrogation time long.

Apart from the emergence of atomic frequency standards from the laboratory out into the field, including into space, the other main development came with the discovery of

laser action around 1960, and the extension of coherent frequency techniques and measurement to the far-infrared and mid-infrared, and later to the near infrared and visible regions and beyond (Jennings et al 1986).

The atomic frequency standards themselves have benefitted from the use of lasers. The laser-cooled caesium fountain - a primary standard - has now an accuracy (single-sigma uncertainty) of about ± 3 parts in 10^{15} , about 30-100 times better than laboratory caesium beam standards (Clairon et al 1996).

The wide spread of the use of local atomic or other comparable frequency standards has transformed the user scene from 40 years ago. Almost all accurate navigation and control systems operate with local frequency standards, if we include quartz crystal oscillators. Indeed the cheapest wrist watches have quartz crystal oscillators and are capable of the accuracy attributable to naval chronometers 40 years ago.

In roughly chronological order the emergence of atomic frequency standards from the laboratory has gone as follows. First, as we noted above:-

- (i) The International Atomic Timescale TAI was operated from about 1958.
- (ii) The world practical atomic timescale UTC was formally adopted in 1975.
- (iii) Broadcasting transmitters, especially those at VLF, up to about 200 kHz were put under control of Cs or Rb frequency standards, in order to disseminate frequency, as with the 200 kHz transmitter at Droitwich in the UK. Dedicated receivers which phase locked on to the received signals, and perhaps with a local quartz crystal oscillator, acted as "off-air" standards of frequency. National time codes were also broadcast under caesium control, such as by MSF at 60 kHz from Rugby, England, or by DCF at 77.5 kHz from Mainflingen, Germany, to act as main routes for dissemination of standards.
- (iv) Scientific experiments utilised frequency standards, e.g. on gravitational red shift and general relativity, by launching a hydrogen maser into space on a rocket and tracking its signals from the ground, in 1976 (Vessot et al 1980).
- (v) The development of laser frequency measurement, starting with the far-infrared in 1967 (Hocker et al 1967), proceeded rapidly until a measurement on a stabilised laser at 88 THz (Evenson et al 1972) in the mid-infrared, supported by another at 30 THz (Blaney et al 1973), provided a value for the speed of light limited in accuracy only by that of the existing length standard. The new value was adopted in 1973.
- (vi) The further extension of laser frequency measurement to the visible (Pollock et al 1983, Jennings et al 1983) then in 1983 permitted the adoption of a new definition of the metre in which the speed of light became a fixed constant, unchanged in value from 1973.
- (vii) At this point, 1983, retrospective to 1973, there was no longer any loss of accuracy in converting from time of flight optical distance measurements to metres. However the metrology of optical lasers used for length measurements in the laboratory required the measurement of their frequencies.

(viii) In telecommunications the terrestrial networks changed to synchronous digital networks working under the Synchronous Digital Hierarchy (SDH) rules adopted by the ITU about 1990, based on those drawn up in the USA for SONET (Synchronous Optical Network) after 1985. Such networks have a hierarchy of frequency standards at distributed points. Caesium clocks met the main requirement for a <1 part in 10^{11} frequency reference, and an advanced quartz crystal oscillator of the BVA type met a lesser requirement (Kartaschoff 1991).

(ix) Optical fibre communications developed following the discovery of low-loss propagation in silica fibre at 1300 and 1500 nm wavelength. (An O-H absorption interferes with use at 1400nm.) Frequency standards for coherent communication using frequency division multiplexing have been called for and provided (Knight 1996), mainly for the 1500 nm band, and the ITU about 1995 laid down frequency channels to be used for international purposes. These are spaced at 100 GHz intervals from 193.1 THz (ITU Telecommunications Standardization Sector 1995).

(x) Optical communication in space has developed, especially for high data-rate applications. The sources used are typically high-efficiency lasers, such as the GaAs laser and its derivatives near 850 nm and the diode-laser pumped Nd-YAG laser at 1064 nm.

(xi) Closely related to VLBI is the tracking of space craft in space, especially in deep space, as by the Jet Propulsion Laboratory's (JPL's) Deep Space Network (DSN), with the main base in California and others around the world. The requirement for frequency standards at the ground stations is of the order of 3 parts in 10^{14} (single sigma) (Deep Space Network 1993), and a novel combination of a cryogenic sapphire oscillator and mercury ion-trap standard operating at 40.5 GHz is being applied to the task (Prestage 1998).

(xii) Terrestrial mobile communication networks increasingly use e.g. rubidium frequency standards, as by some police forces in the UK (c1990), and they are likely to be found in space-borne equivalents such as Motorola's Iridium system. One reason for increased use of accurate standards is that air-wave space is increasingly congested, and problems of out-of-band emissions have to be controlled. As frequencies have risen above 1 GHz the relative channel spacings have diminished, and there are for example problems of interference with neighbouring radio-astronomy bands, as occurred with GLONASS (Ponsonby 1991).

A2.4.2 Impact of delivering time better over the years

The more general use of absolute time has been slower to develop than the spread of accurate frequency standards into, say, communications. However, today, in 1999, many systems which are under electronic automatic control are moving towards **absolute time control** as well. Among the more obvious applications are secure communications and systems used to measure distance, such as for navigation and positioning (GPS is a prime example, Loran-C was an earlier one) and collision-avoidance systems. The use of absolute time assists with safety and security checks, and can contribute economy and

order to the use of communication channels. For example absolute time codes permit all the 24 GPS satellites to transmit on the same frequency and yet be discriminated by the user.

In roughly chronological order, notable developments in the use of **absolute time** have been:-

(i) The introduction of atomic timescales, of TAI in 1958, and the general adoption of UTC in 1975.

(ii) Time dissemination by broadcasts under caesium control at VLF from terrestrial stations such as WWV, MSF and DCF.

(iii) Time dissemination via satellites using caesium ground stations, such as by GOES (Geostationary Operational Environmental Satellite) in the USA (Ellis 1988), via TV broadcasting satellites in Europe for common view (Pearce et al 1990), and for accurate two-way time transfer using telecommunication satellites with the Hartl modem (Hartl et al 1983).

(iv) Navigation systems using terrestrial broadcasts under caesium control and exact timing usually at VLF or ELF, such as Loran-A, Loran-C and Omega (Ellis 1988).

(v) Satellite-based navigation systems such as the US Navy's TRANSIT system and now the US GPS (Global Positioning System) and the Russian GLONASS equivalent. The latter systems, whilst primarily military, offer immense practical benefits to all users world-wide. At the cost of order 150 ecu a pocket-sized GPS receiver can be purchased which will give one's position anywhere in the world to 100 metres or so. Much more precise positioning is possible with access to the two-frequency system, which offers real-time ionospheric correction and positioning accuracy of a few centimetres. Differential use also increases accuracy in a given locality. Such is the success of the GPS system that it has occasioned a great revision of mapping around the world, and contributed to geophysical studies. The system measures time intervals and has caesium standards or equivalents on the satellites. UTC(USNO) is available on the readout from the receivers to microsecond or better accuracy.

(vi) The development of low-cost "radio clocks" and watches (Boullin 1988) working from the terrestrial VLF time-code transmitters such as DCF and MSF, notably by Junghans of Germany about 1988, has brought accurate time into the home directly. (Time is also brought by radio and TV, but involves human activity in setting clocks). Such radio clocks automatically correct for summer time and winter changes, and can save expense in an office or public environment in this respect. The time accuracy is about 1 ms. A similar, company-operated system is used to control clocks in electricity meters in the UK, and use in similar systems might spread.

(vii) Mobile communication and paging networks: the Pan European Paging network called for synchronisation of its stations to 10 microseconds, now possible using GPS.

(viii) Some secure communication systems, e.g as used by the military, call for absolute time synchronisation.

(ix) A sufficient degree of time synchronisation is required for VLBI and satellite ranging as with the DSN. When the stations are widely separated this amounts to requiring absolute time at each station, in addition to the requirement for a frequency standard to act as a timing "flywheel".

To sum up, the take up by users of accurate timing, apart from sophisticated users such as the hyperbolic and satellite navigation systems, is of recent origin, and is connected with the development of cheap microelectronics. The only specifically optical timing application is for ranging, terrestrially and in space (Degnan 1997), where the beam-forming and propagation benefits of the short wavelength dominate, and the existence of optical technology such as efficient and powerful lasers makes systems potentially smaller and cheaper than in the microwave.

Appendix 3 Frequency standards and microwave to optical intercomparison and frequency chain work

A3.1 Comparison of principles of sources, oscillators, frequency standards and clocks in the microwave and optical regions

For a frequency standard there are three main elements: the **oscillator**, **servo** and **reference resonance**.

Regarding the **oscillator**, the near equivalence of the maser and laser offer no difference, except that in the optical region devices such as resonators can be much smaller and lighter, size being proportional to wavelength. There is little difference in power-conversion efficiency between solid-state microwave sources and solid-state diode lasers.

For the **servo**, control in the optical can be fed back directly or via modulators, as in the microwave. Electronics may need to be faster, as the oscillator frequency is much higher. However, optical-feedback spectral narrowing in the optical counters the need for this. There appear to be no major differences in the matter.

For the **reference resonance**, the Q s in the optical can be very high, as they also are for the H maser in the microwave (10^9). Indeed with ion traps very long upper-state lifetimes give theoretically enormous Q s, but in practice these are limited by the need to interrogate the reference resonance, typically every few seconds. The existence of the much higher frequency in the optical region offers fast assessment of all factors affecting a frequency standard, e.g. of external perturbations, using frequency counters rather than a phase-detection system as is required for the H maser at 1.4 GHz. A beat signal between H masers might be at 1 Hz, where one between lasers might be at 100 MHz, offering 10^8 higher resolution in 1 s. With 1 Hz resolution in the visible the discrimination of frequency is about 1 part in 10^{14} or better, but it is usually more limited by oscillator fm noise. In addition to high frequency and high Q , the optical region offers high signal to amplitude noise. Amplitude noise can be cleaned up by "noise eaters". One method of cleaning up frequency and phase noise is by locking to resonances in rigid cavities, made of low thermal-expansion materials and with "super" low-scatter Fabry-Perot (FP) mirrors. (The latter were developed in the past 20 years for laser gyros.) Pre-stabilisation by this method also permits the use of modulators to take out frequency and phase noise against even better references, such as the very-high Q resonators used for gravitational wave detection, as in various terrestrial experiments such as VIRGO (Caron et al. 1997), GEO600 (Luck 1997), LIGO (1993) and the LISA proposal for space (Bender et al 1998). Most optical frequency standard systems are passive, with short-term fractional-frequency noise decreasing as $\tau^{-1/2}$ unlike, say the H maser (τ^{-1}), but the high optical Q s and new cryogenically stabilised references to which they might be locked offer altogether lower noise, with the expected lower flicker floors (Gallop 1996), including a demonstrated stability for a 1064-nm Nd-YAG laser of < 1 Hz over 20s (Seel et al 1997).

A3.1.1 Oscillators

There have been many developments in low-noise (sufficiently) tunable oscillators for the microwave, from solid state, such as the BVA quartz crystal oscillator, offering a σ_y of 3×10^{-13} at 1s, this being really a "flywheel" to use with longer term standards such as the caesium beam or fountain, also SAW (surface acoustic wave) quartz oscillators available at higher frequencies with lower phase noise (as used in the HP 5071A caesium standard), GaAs FET amplifiers, YIG filters, and so on, but none of them making dramatic improvements.

In the optical there are highly coherent sources as it were "looking for work". Perhaps the best example is the solid-state Nd^+ -YAG laser with its strongest line at 1064 nm. In the diode-laser pumped form it is extremely efficient, spectrally narrow and indeed powerful, the pump diode laser systems can have emissions of order 100 W. Solid-state diode lasers with extended cavities for improved coherence already provide compact and portable frequency standards in the near infrared e.g. locked to rubidium at 780 nm (Barwood et al 1993) and more accurately, 10^{-11} , at 778 nm (Touahri et al 1997). In addition gas lasers in standards where they are locked to saturated-absorption features in e.g. I_2 cells, can be replaced by extended-cavity narrowed diode lasers (Edwards et al 1998), much reducing the power required and greatly increasing the expected optical life.

A3.1.2 Servos

Since most optical standards will involve locking an oscillator to a passive resonance, the development of optical versions of the nearly ideal microwave Pound stabiliser system (1946) such as the Pound-Drever system (Drever et al 1983) avoids any particular difficulty with the optical. It should be noted that the extreme preoccupation with suppressing noise in optical-resonator gravitational-wave detection experiments has created a body of knowledge in which the art of servo-control (and of environmental isolation) has been pressed to limits corresponding to fractional frequency deviations of 10^{-17} or lower (Ward et al 1985) in desired spectral regions.

A3.1.3 Reference resonances

Again, there is no particular disadvantage of the optical over the microwave:-

- (1) Strong, saturable transitions exist.
- (2) Several laser-cooled atom or ion long-lived transitions can be accessed.
- (3) There are no clear disadvantages of having dominant shot noise (optical) over Johnson noise (microwave) in the two regions, indeed shot noise can be significant in microwave standards too, from noise on particle beams or from excitation light (Hellwig 1975). Kramer of PTB has considered the noise of passive frequency standards, including an ensemble of N particles in a trap, and shows the square root law in statistics

leads to short-term noise proportional to $1/f_0$, indicating that going to as high a frequency as practicable is best (Kramer 1996), also that a single cooled particle in a trap appears to be the "ultimate proposition" for accuracy.

What then are the inhibitions in developing optical frequency standards and clocks?

1. The development of optical frequency standards (and clocks) has now been in progress for 40 years since discovery of the laser. In about the first decade stabilised cw lasers at accuracies of order 10^{-10} - 10^{-11} were put in place, and frequencies up to 88 THz measured. In another decade frequency measurement (by chains of lasers) reached the visible and better stabilised lasers at $\sim 10^{-12}$ (hyperfine-resolved methane, and OsO_4 -stabilised CO_2) became available. In the next decade the technology shifted away from gas lasers to solid state, and in parallel entirely new standards were produced based on the laser cooling and trapping of ions and atoms. The idea of a single particle resonator held stably in the laboratory frame free of first- and second-order Doppler effect took the imagination. In the most recent decade the ion trap has come to fruition in the high microwave, with the NIST 40.5 GHz $^{199}\text{Hg}^+$ standard having performance exceeding existing measurement capability at 1 part in 10^{14} (Berkeland et al 1998). In addition, the use of laser-cooled caesium atoms has advanced the art of the primary standard to 3 parts in 10^{15} (Clairon et al 1996).

In the optical, the techniques of absolute frequency measurement have been applied to H atoms in beams to measure the fundamental 1S-2S electronic transition at 2466 THz, 121.6 nm, achieving an accuracy of 3 parts in 10^{13} (Udem et al 1997). This is within a factor 30 of the limit of practical microwave frequency measurement, above. Early experiments on trapped ions in the visible, requiring narrow and precisely controlled lasers, have accessed transitions with excited-state lifetimes up to 3700 days (Roberts et al 1997). Such experiments are fundamentally aimed to surpass existing standards, looking towards accuracies in the 10^{-17} range, of which they are capable in principle (Wineland 1986). Applications forseen in basic physics such as the detection of gravitational waves (Will 1977) require such accuracy.

The chief inhibition regarding optical frequency standards and clocks is clearly the problem of relating the optical frequency to frequencies in the microwave region by e.g. a phase-locked frequency-divider "chain". This is necessary for distributing frequency standards in the rf region and for operation of clocks taking full advantage of the optical frequency standard.

Until recently, (i) a large assembly of equipment was needed to make an accurate frequency transfer from microwave to optical or vice-versa. (ii) direct phase-locked connection only extended from microwave to 30 or 88 THz. However, as is discussed in the next section, developments in physics laboratories now point towards a much more compact system of absolute frequency "division", which is capable of operating from the visible or near-infrared to the microwave (Luiten et al 1998). Also, if lower accuracy is acceptable in the microwave, a simple spatial method of transfer can be applied in which a microwave signal is locked to the optical one via a common resonator. These issues are discussed next.

A3.2 Microwave-to-optical intercomparison and frequency chain work

There are two options for comparing frequencies in the the rf and microwave traceable to the caesium standard, with frequencies in the optical region, say from the far-infrared at 1 THz to the visible at 500 THz. The choice is between spatial comparison and time-domain comparison. In the former, effectively the wavelengths are compared, and in the latter frequency multiplication or division takes place, using harmonic generators or frequency multipliers known by other names, such as "comb" generators. The limitations in the spatial method are from (i) diffraction at apertures, imperfect co-alignment etc., and (ii) from differential phase shifts at reflecting or refracting components. Both may vary from e.g. temperature or aging effects and so give time-dependent errors in the derived frequency ratios. For maximum accuracy only the time-domain method suffices, although this too can suffer from low signal/noise effects on account e.g. of high multiplication in the presence of phase noise, resulting in phase-lock cycle slippage etc. The apparatus for the latter method is much more complex than for the former. Much depends on the accuracy required, especially for clock operation.

Method 1. Spatial

Spatial measurement of an optical frequency was carried out in the first laser speed of light experiment, that achieved an accuracy for c_0 of about 6 parts in 10^8 (Bay et al 1972). A microwave frequency near 10 GHz was carried on sidebands modulated onto the visible frequency required to be measured. By locking an external Fabry Perot (FP) cavity to the microwave sideband spacing (both sidebands equally transmitted) and then locking the optical carrier to the resonator (both sidebands maximally transmitted) the optical and microwave frequencies are forced into a near integral relationship (Bay et al 1972). The frequency-ratio accuracy was 6 parts in 10^8 and was dominated by random noise rather than by estimated-quantity uncertainties.

Later experiments by DeVoe and Brewer (1984) using a dual-frequency modulation technique much improved the signal/noise, and they estimated an absolute accuracy for the frequency ration of 2 parts in 10^{10} , if superpolished mirrors were used and the cavity phase shift corrections were measured (DeVoe et al 1984). One technique was to calibrate cavity phase shift effects by locking lasers to adjacent transmission orders and measuring the frequency interval across a wide span of modes. A fit to the measured reflection phase shift allowed more precise correction. Their cavity length was 0.5 m, but they remarked that using long, e.g. gravitational-wave detection cavities, would increase accuracy proportional to length, see e.g. the LISA proposal (Bender et al 1998). If a clock signal desired from an optical frequency standard required mainly medium-term stability rather than low short-term noise, such a method of creating it might be useful.

Super-reflecting optics and ultra-low expansion (ULE) ceramics can be applied to construction of the relating resonator, although it does need an electronic tuning range sufficient to cover the extent of expected drifts of its parameters.

Method 2: Time-domain frequency multiplication and division

At the outset we should note that at laser frequencies the only system giving **true frequency division** is the optical parametric oscillator, and in practical cw instances it is limited to divide-by-2 or (just) divide-by-3 action. It has been tested to 5 parts in 10^{18} (Ikegami et al 1996). Division can be achieved however by the use of frequency multiplication and frequency mixing and feedback phase-lock loops, so that the low frequency oscillator is controlled by the high frequency one (Blaney et al 1971). Such "division" can be at very high frequency ratios. Multiplication has been demonstrated directly from a quartz crystal oscillator at 120 MHz to beat with a laser at 2.5 THz (Blaney et al 1976), and a 99 GHz klystron has been locked at its 43rd harmonic to a laser at 4.25 THz (Blaney et al 1980), both using Josephson junctions.

A. Frequency- multiplication chains

The bulk of laser frequency measurements have been made entirely using chains of lasers at successively higher frequencies, multiplying the frequency of each to the one above (Jennings et al 1986). The most accurate frequency standards, of the saturated-absorption in gas cell type, fall in the mid-infrared, in the 30 THz, 10- μ m region and at 88 THz, 3.39 μ m for the most accurate of all, the hyperfine-resolved methane stabilised laser (Knight 1997).

All the early work of frequency standard measurement used the metal-insulator-metal (MIM) point-contact diode as the main harmonic mixer (Knight 1976), but this reaches its convenient limit of harmonic generation at about 150 THz, 2 μ m (Pollock et al 1983). Beyond this, multiplication and mixing is by frequency doubling and sum and difference-frequency generation in phase-matched bulk crystals. (Until recently the lack of amplifiers, coupled with low efficiency of doubling, made it difficult to have more than one such stage in series.) By this means the less accurate but much used red He-Ne/I₂ frequency standard at 474 THz, 633 nm was measured in absolute frequency (Jennings et al 1983). Until now the optical measurement chains have not covered the whole span from the microwave to the visible, but either go from microwave to the accurate lasers in the mid-infrared, or from the latter to the visible. (One microwave to visible chain was planned at NPL but not completed (Knight et al 1985)).

Although laboratory optical "clocks" have been demonstrated from the 88-THz methane-stabilised laser (Bagaev et al 1983, Weiss et al 1989), the lack of a direct frequency chain could be an impediment to an optical "clock" working in the visible. However, recent developments with reported optical "divide-by-2" stages and optical comb generators offer suddenly a new way of doing this (Hänsch 1998), which we discuss next.

B. All-optical frequency division and comb generation methods to compare with microwave frequencies

One of the difficulties of high-optical to microwave frequency linkage is that the technology changes in the mid-infrared. There is some advantage technically in frequency synthesis with a unified technology in achieving elegance and economy in the frequency transfer, as was demonstrated at the National Research Council, (NRC),

Canada, by Whitford (1984), who used an entirely CO₂-laser based chain for measurements to 88 THz. He used difference frequencies between CO₂ lasers to replace the lower-frequency far-infrared transfer lasers used elsewhere, and fully phase locked the whole system (Whitford 1984).

Starting from the visible, one can use new technological development in crystals for nonlinear mixing in the visible and the near-infrared, the region of the 1064 Nd⁺-YAG laser, which, it should be said, can be used as a frequency standard when frequency doubled and locked to an I₂ absorption in the green (BIPM 1998). Much development work has gone into crystals such as lithium niobate or KTP, and suitable cut and coated pieces are now available from countries such as China and Russia.

The fundamental-physics experiment carried out to measure the frequency of the 1S-2S line of hydrogen at 2466 THz, 121.6 nm, can be used to illustrate the new developments (Udem et al 1997). This was done in two parts. First, a very good methane stabilised laser was taken as a frequency standard (specially measured for the occasion) and its frequency multiplied by the conventional "chain" (by 7) until near a 487-nm laser locked at the 4th sub-harmonic of the 1S-2S transition.

The second part was to measure the difference frequency between the 7th harmonic of the 88-THz laser and the 487-nm laser. The difference was 2.1 THz. Its frequency was successively divided by 2 by the method of inserting a third laser half way between the two extreme ones (using a summation crystal, a doubling crystal and a phase-lock loop (Udem et al 1997)), repeatedly, until the divided frequency interval reached a value ~ 66 GHz that could be output from a fast photodiode and measured by microwave techniques. The frequency division part of the experiment was done entirely in the optical using several diode lasers, and points the way forward for optical clocks.

In principle any absolute frequency can be turned into a frequency interval suitable for the divide-by-2 process, by doubling the frequency and using the interval between the fundamental and second harmonic. In the early stages the divide-by-2 process might be more difficult because different crystals or cuts might be needed to accommodate the widely-spaced frequencies, but as the difference becomes smaller, the same crystal can be reused for successive stages of the division, and so achieve economy.

The measurement of the final interval is also possible by comparing the lasers with the extremities of "comb" sidebands generated on an optical carrier nearby. The comb can be accomplished (Wong 1992) by strongly modulating an optical signal with a microwave frequency between about 5 and 20 GHz. (It is important to obtain "true" comb sidebands, not those representing modes of say a mode-locked laser, since dispersion in the laser medium would alter the comb intervals towards the extremities.) A recent test of a modulator comb against repeated divide-by-2 stages has proved both methods to about 7 parts in 10¹⁵ (Udem et al 1998). Comb measurements have been applied to optical communication standards in the 1300-1500 nm region (Saitoh et al 1996).

A new prospect is to use the sideband radiation components of a femtosecond (Ti-sapphire) laser as a "comb". Preliminary tests have indicated usable sidebands at harmonics of the repetition rate out to a tested span exceeding 20 THz (Udem 1998) and

approaching 44 THz (Hänsch 1998), half the frequency of the methane stabilised laser, and a factor 10 or 20 greater than achieved by the modulator method.

Given such a comb generator all that would be necessary to measure the methane stabilised laser frequency would be one divide-by-2 stage between two of its adjacent harmonics in say the visible, and a femtosecond laser comb set to span the divided interval. Measurement of the two beat signals and the repetition rate of the femtosecond laser, all at rf or microwave, would complete the measurement of the methane stabilised laser frequency.

If it were possible to pull the femtosecond laser's repetition rate a little without disturbing its action, then in principle phase-locked division of a laser frequency is accomplished entirely in the visible to near-infrared region.

In summary, we can look to fast-moving developments in optical science to provide all-optical frequency division to rf on a timescale of a decade or two, in which optical standards may be brought into general scientific use and be prepared for use in space.

Appendix 4 Moving from the microwave to the optical

A4.1 Trends in applications technologies towards the use of higher frequencies over the past 40 years

A number of critical changes have taken place in science and technology over the past 40 years. We might note that the first earth satellite, Sputnik, orbited in 1957, the first microelectronic silicon chip was made in 1958, the laser came into being about 1960, the first telecommunication satellite, Telstar, was launched in 1962, the Apollo moon voyages took place in 1968-72, and the first Global Positioning System satellite went up in 1978. More recently there have been widespread use of optical fibre in terrestrial telecommunication systems, and development of cellular-network mobile telephones working at low microwave frequencies, throughout the industrialised nations of the world.

To look at the progression in the use of higher frequencies, and particularly for space applications we shall consider (Bay et al 1968) frequency standards and frequency measurement, (Froome 1958) ranging, and (Froome and Essen 1969) the increasing use of absolute time in systems.

A4.2 Frequency standards and measurement

The standard of time interval, the second, and consequently of frequency, now called the hertz, was defined with respect to an atomic caesium transition in 1967 (Allan et al 1997). Since that time, apart from increasing use of atomic frequency standards in the field for telecommunications, navigation and ranging, the main change in the use of the frequency spectrum came from the invention of the laser - a light source with behaviour like that of a radio-frequency oscillator - and consequently the extension of frequency measurement upwards beyond the microwave to laser frequencies (Jennings et al 1986). The first laser frequency was measured by harmonic generation and beating techniques in 1967 (Hocker et al 1967). With the Doppler-free stabilisation of lasers by saturated absorption in gas cells at 10 μm (Freed et al 1970) and at 3.39 μm (Barger et al 1969), such lasers were soon measured against the caesium standard and became frequency standards in their own right (Evenson et al 1972, Blaney et al 1973). Frequency measurements were later extended to the red He-Ne laser locked to iodine (Jennings et al 1983). This stabilised laser (Hanes et al 1969) was used for many years as a length standard and has since been joined by many other lasers with frequencies recorded for that purpose (BIPM 1998).

The accuracy of laser frequency standards, and the accuracy of their frequency measurement, has much increased from the initial part in 10^9 level so that recently 3 parts in 10^{13} was achieved for the hydrogen atomic 1S-2S transition at 121 nm, 2466 THz (Udem et al 1997). The latter accuracy is within a factor 30 of the international realisation of the Hz (Thomas 1997). Laser cooling and trapping of atoms and ions has brought prospects of much better frequency standards from microwave to the optical. Optical standards have the ultimate advantage because of their higher frequency resolution and because of the higher Qs of their transitions (Hellwig 1984, Kramer 1996). A survey of laser frequency standards lists the more accurate ones across the

spectrum (Knight 1997), in addition to those listed by the BIPM in connection with length measurement (BIPM 1998).

There is specialised interest in frequency standards for the optical-fibre communication bands at 1.3 and 1.5 μm (Knight 1996), in particular at 1.5 μm for coherent WDM/FDM systems, for which frequency band allocations have been made (ITU 1995). Commercial WDM/FDM equipment is being installed as fast as it is produced, by internet and other computer traffic carriers (Arie 1998). The practical requirement for frequency standards for the latter application emphasises operational hands-off life, compactness and low power demand, paralleling some demands of practical space applications, with accuracy in the field of the order of 1 part in 10^9 (Knight 1996).

Fundamental scientific experiments have involved flying accurate frequency and time standards in space. In 1976 a hydrogen maser was launched into space on a rocket, and it acted also as a "proper" clock in its relativistic frame, for a precise measurement of the second-order relativistic Doppler shift and gravitational redshift of its frequency (Vessot et al 1980). In 1978 the first of the constellation of 24 GPS satellites went up, each carrying accurate standards such as caesium or rubidium for the practical purpose of accurate navigation and positioning. Present plans involve flying two hydrogen masers on the Space Station by ESA/NASA in the forthcoming ACES experiment, see e.g. Vessot 1997, and preparatory work on a laser-cooled caesium standard for space (Laurent et al 1998). It is expected that clocks flown in space near the earth will perform better than on earth because of the reduced environmental perturbation.

For deep space missions, standards providing stable frequencies allow one-way Doppler shift measurement, as for the Huygens Probe relative to the Cassini orbiter in the Doppler Wind Experiment (DWE) of the joint NASA/ESA deep space mission Cassini/Huygens to Saturn and its moon, Titan (Kohl and Bird 1997). Rubidium standards are used for the first time on a deep space mission to keep both the descender Probe transmitter and the orbiter receiver reference frequencies within 2 parts in 10^{10} during the Probe's descent through the Titan atmosphere under stressful conditions.

A4.3 Ranging

In the 1950s there was much effort to maximise the accuracy of microwave and optical ranging techniques aimed at geodetic survey in the earth's atmosphere. For one thing, it was important to replace the labour-intensive and less accurate invar tape method, and for another the convenience of trilateration at distances up to 50 miles offered much greater accuracy and greater speed than the foregoing triangulation method over eye lines of sight. A definitive measurement of the speed of light in vacuum was achieved by Froome at NPL using 4-mm microwaves (Froome 1958, Froome and Essen 1969).

Shortly after this the first laser speed of light measurement was made (Bay et al 1972), involving an interferometric frequency ratio determination between microwaves and a visible stabilised laser (Bay et al 1968), closely followed by true frequency-chain measurement of a 3.39 μm stabilised laser (Evenson et al 1972) giving a speed of light value limited by the reproducibility of the length standard (CCDM 1973). This speed of light value was of immediate use for converting lunar time-of-flight ranging to metres. It remained unchanged when the metre was redefined in 1983 by adopting the speed of

light in vacuum as a fixed physical constant (BIPM 1984). Thus the scene was set for ranging in space with the same accuracy as could be achieved in the laboratory, limited only by the (very high) reproducibility of the caesium standard of time interval.

Lasers have been used to range satellites from the earth from the beginning of space activity, see, for example, a report of the Second Conference on Instrumentation for Laser Tracking of Space Objects, held in 1975 (Kokurin et al 1976). Following placing of reflector arrays on the moon by the Apollo astronauts c1968, the distance of the moon has been continuously monitored. Also one of the first uses of satellites was to investigate the geophysical and gravitational properties of the earth, for which corner-cube reflector-array satellites such as Lageos were placed into orbit (Bears 1976). This work has been refined and has reached an accuracy of at least 200ps (6 cm) in the LASSO experiment (Veillet 1991), in which laser pulse timing has been used to check time transfer by the widely-used GPS common-view method using high rf frequencies, and the spread-spectrum telecommunication satellite method using microwave frequencies (Hartl et al 1983).

As a precursor to use of optical signals for deep space missions, laser signals from earth were transmitted to Galileo in December 1992 out to a distance of 6 Gm, 15 times the earth-moon distance (Wilson et al 1993).

A4.4 Use of absolute time in systems

Until very recently the main users of accurate "absolute" time, i.e. accurate use of UTC or of TAI, were electronic navigation systems, such as for many years the Loran-C and Omega VLF systems, recently supplanted in general use by the GPS satellite system. All these ran on caesium-derived timescales initially in synchronism with UTC, but not applying the subsequent leap-seconds of UTC. Local standard accuracy was typically better than 1 μ s. Other users needed typically no better than 0.1 s, e.g. for sextant navigation or positioning, or for synchronising human activities. Automatic radio clocks became available about 1988 (Boullin 1988) having about 1 ms accuracy, and at this level time could be cheaply supplied to electronic systems, such as computers, also by telephone. In such dissemination systems there is no correction applied for the propagation time from emitter to receiver.

Other terrestrial users of accurate time are power network companies concerned to control the phases of generators connected to the supply network, and operators of multi-station telecommunication systems, such as cellular networks. The Pan-European Paging Service (Knight 1992) called for synchronisation of neighbouring stations to within 10 μ s. In the international telephone networks the SDH specifications call for caesium frequency standards at critical points, to allow synchronisation (Kartaschoff 1991).

The fortunate arrival of the GPS and GLONASS satellite navigation systems, which work with absolute time and time-of-flight distance measurement, allows provision of time at about the 100-ns level to any users within range of the 27000-km radius orbits, including continuous coverage of almost all the earth's surface, see for example Kramer and Klische 1997. With these, the propagation time is corrected in real time, to adjust

the user's clock to the system time. (The system works by receiving signals from 4 satellites and solving for the receiver's x , y , z and t coordinates).

Since both GPS time and GLONASS time are traceable to UTC within about 100 ns, these systems allow terrestrial networks to achieve the necessary relative synchronisation by in fact adopting absolute-time synchronisation, which is extremely powerful and robust, in engineering terms. There is not the risk of say a master reference failing and causing all its slaved systems to fail.

The laser ranging of satellites from the earth, as we have seen, has progressed to using the ranging accuracy as a timing accuracy to check methods of time transfer at rf and microwave frequencies (Veillet 1991). A further improvement is involved in a package proposed for the MIR space station, in which a laser pulse transponder is connected to an on-board clock, and the arrival time of pulses recorded. Since MIR is in low orbit, ground stations at wide separation cannot illuminate it at the same time, so the on-board clock "stores" the time from one illumination time to the next. The accuracy for comparing two ground clocks is estimated at 50 ps (Samain 1997). The chief attraction of this high accuracy is that it would permit definitive intercomparison of the new generation of laser-cooled primary standards having accuracy near 2 parts in 10^{15} , which in turn will give a better TAI timescale. At present international frequency measurement can only be realised from TAI to about 1 part in 10^{14} (Thomas 1997).

For remote space vehicles, the maintenance of accurate time on board allows one-way rather than return-signal ranging, as occurs routinely since 1978 with the GPS and GLONASS satellites. Deep space applications include testing aspects of General Relativity, and in a Small Explorer (SMEX) mission study, a linear ion trap standard (LITS) has been proposed as the only suitable atomic clock (Maleki 1997). Since a LITS clock is in the medium term the best available (Prestage 1998) it is an implication that in future optical frequency standards might be preferable because of their yet greater potential accuracy.

A4.5 Trends in implementing optical technology: transitional development towards all-optical hierarchy

We have remarked that optical communication experiments in space are in progress by NASA (Lesh 1998) and by ESA (Lutz 1998) and a great deal of research has been addressed to this, see e.g. the SPIE annual conferences on Free-Space Laser Communication Technologies which began in 1988, and the Journal "Space Communications".

Terrestrially, the use of optical fibres grows quickly, as noted in the introduction, and telecommunication network planners and engineers look to a "new paradigm", all-optical exchange to exchange system, and perhaps right through to users. Optical fibre systems first are the only way to meet current demand for computer-based communication and provision of fast internet access to end users. The flexibility of having bandwidth to spare allows easy updating by putting in WDM/FDM systems on the existing transmission links (at $1.5 \mu\text{m}$). It can also take the pressure off microwave multiplexing and demultiplexing systems, which have reached a stage prone to software failure as much as hardware failure. The technical problems of all-optical systems are

being solved, such as the introduction of reliable wide-band fibre amplifiers, and optical multiplex/demultiplex systems such as used for WDM/FDM. The transmission losses are so small compared to copper and the multiplicity of optical fibre paths is rapidly increasing since all long-distance networks, from canals to gas to electric power are adding fibre links to all their new connections. From the point of view of terrestrial telecommunications the move to optical appears to have no immediate problems and technical development is now providing a rapid and large increase of capacity.

In space, experiments have been conducted towards using optical systems under zero-gravity conditions. A French group has flown a laser-cooled caesium frequency standard in aircraft at zero g, to prove that the solid-state lasers and the whole device worked satisfactorily (Laurent et al 1998). The frequency standard was flown for a total of 30 minutes at reduced gravity, and its potential frequency accuracy estimated at about 5 parts in 10^{17} in space as opposed to 2 parts in 10^{15} on the ground (Clairon et al 1996) - about an order of magnitude improvement.

It must be noted that the optical component industry is much less developed than the microwave one for space applications, since the latter is still in the research phase - but the high reliability technology being developed for terrestrial fibre-optical networks should transfer rapidly to space applications when required.

For the ground segments of space systems, optical techniques increasingly supplement the microwave in photonic devices. Optically generated and carried microwave signals are increasingly used, and a notable application is in providing phase control to microwaves feeding phased-array antennas for rapid angular sweeping and shaping of the beam (Graydon 1998). An optoelectronic device providing optical and microwave oscillations with coupled phases (Yao and Maleki 1997) has potential use in mainly optical systems.

Appendix 5 Conference Paper: ULTRA-STABLE OPTICAL FREQUENCIES FOR SPACE*

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ABSTRACT

Attracted by the prospect of vastly increased bandwidth, a move from the microwave to the optical for space-based communications is now underway. It is important to consider the associated optical frequency source requirements. "Direct detection" systems have been considered for the first phase of commercial inter-satellite optical-communication links. "Coherent communication", which offers at least an order of magnitude improvement in capacity, requires spectrally narrow sources, and is more difficult to implement. Ultra-narrow lasers will be needed for low data-rate applications such as the deep-space network (DSN). The required stability and accuracy of the lasers will also depend on the additional demands of any navigation, tracking and "radio/light science" functions served. Cavity-stabilised narrow lasers are expected to be the basis of the best laser oscillators operating in the optical for space applications.

1. INTRODUCTION

Terrestrial telecommunications moved from the microwave to optical carriers for long-distance transmission with the advent of compact diode lasers and lightweight low-loss fibre: these optical systems offer much higher bandwidths (potentially up to 25 THz) and cheaper transmission. There are many reasons why optical communication systems will supplement microwave-based systems for inter-satellite and other space applications. With much higher frequency (about 100,000 times greater) the optical, when compared to the microwave, has the potential for a commensurate increase in both frequency accuracy [1,2] and bandwidth or information-carrying capability. Coupled with factors such as improved directionality for transmission (for example, the Voyager spacecraft mission to Saturn would have a beam over 2 million times more concentrated using optical systems [3]), lower equipment mass and dimensions, lower power consumption and higher detector efficiencies, with secure communication links, optical technology for space application appears very attractive.

In addition to communication requirements, there are other compelling arguments for developing ultra-stable optical frequency sources and detectors for use in space. At present, the microwave radiation is not only used for communication and navigation/tracking, but also

sometimes for scientific experiments collectively referred to as "radio science" [3]. As the switch from microwave to optical for communications proceeds, the component technology will find other uses in navigation, earth observation, inter-satellite synchronisation, and potentially for a whole gamut of aptly-termed "light-science" experiments. Although direct intensity modulation or "digital" (direct detection) has been used for early flight experiments and operational missions, coherent systems will be required for the more demanding applications. Following an outline of the space application of optical frequencies, this paper highlights some of the laser-frequency control technology which will provide the next-generation of optical sources, frequency standards and ultimately even "optical clocks".

2. APPLICATION AREAS OF OPTICAL FREQUENCIES IN SPACE

2.1 Communications

Reports on a variety of projects studying different aspects of space-based optical or laser communications which have been underway over the last two decades in Europe, Japan and the USA are reported in a 1998 issue of Space Communications[4]. The organisations interested in this field range widely from strongly commercial (e.g. driven by multimedia and Internet applications), to the military, to Deep-Space Network (DSN) users. Active project examples include:

- (i) The European Space Agency (ESA), SILEX (Semiconductor laser Intersatellite Link EXperiment) which will transmit 50 Mbps from LEO to GEO using direct detection[5];
- (ii) The US-Japanese "Ground-to-Orbit Lasercom Demonstration" (GOLD) - the first successful bi-directional optical communication with a satellite with rates of up to a Mbps, and;
- (iii) A programme funded by the US Ballistic Missile Defence Organisation will test intersatellite optical communication links[6].

2.2 Navigation, Tracking and T2L2

Tracking system frequency requirements for the DSN are currently 3×10^{-13} at 1000 seconds[7]. Examples might include: (i) satellite missions which pass close to the Sun, for the study of gravitational effects, and checking for variation in the fundamental constants[8]; (ii) occultation-type experiments; or (iii) missions where

precise one- or two-way Doppler tracking of the spacecraft signal is used. The Satellite Laser Ranging 2000 (SLR 2000) mission looks to develop high-bandwidth real-time communication links to Mars in the future. An example of time-transfer by laser-link (T2L2) is the MIR-based experiment which should make it possible to measure the performance of ground-based clocks having a relative stability of about 3×10^{-15} [9], and for the ACES ensemble on-board the ISS against ground-based clocks using T2L2[10]. An important advantage of optical over the microwave for ranging and time-transfer is the immunity to refractive index effects in the ionosphere and solar wind. Dispersion effects from the atmosphere are an active area of research, particularly through the GOLD programme using multi-frequency transmission with up to four carriers, to ameliorate scintillation effects. Anderson *et al.* recently reported an apparent anomalous weak long-range acceleration[11] from Galileo and Voyager satellite tracking data. They suggest that "the Pluto express mission could provide an excellent opportunity for high quality data from very deep-space, especially if optical tracking is used". The GNSS system requires very stable clocks for best performance. These may eventually be optical clocks, related to the microwave via highly accurate phase-locked links[1].

2.3 "Radio" and "Light" Science

A move to the optical for space-based communications opens up the vista of "light" rather than "radio" science experiments[3]. The most stringent requirements for DSN frequency source stability may be experiments which call for 1.5×10^{-15} over 1000 to 3600 seconds for the Cassini mission[12]. A wealth of space-based scientific experiments may benefit from the use of ultra-stable laser sources and better clocks[13]. Two examples of research which would benefit from very well controlled optical frequency sources are given below:

A "Pre-Phase A" Study has already been conducted into the feasibility of launching the Laser Interferometer in Space Antenna (LISA) platform[14], as part of ESA's Horizon 2000 Programme. The LISA objective of detecting gravitational waves will test the laser and interferometer physics package to the limit (typical interferometer stability of 10^{-19} at 10^3 seconds averaging): mHz-wide space-qualified lasers are required[15]. A precursor to an all-optical LISA system might be the development of optical hardware on the International Space Station (ISS): a first step to realising this goal is the ACES (Atomic Clock Ensemble in Space) which includes a laser link for accurate time- and frequency-transfer.

Very-Long Baseline Interferometry (VLBI) systems currently using microwave frequencies and microwave atomic frequency standards for synchronisation are limited by atmospheric propagation of the radiation

through the ionosphere and the troposphere, and the ability to resolve the carrier phase. Two developments are currently taking place. The first proposes to operate an array of satellites in a new Space VLBI network - the Space Interferometry Mission (SIM), bringing better solid-angle resolution and atmosphere-free performance. The second proposal for next-generation European (or global) VLBI is to steer the network with optical clocks either terrestrially (through optical fibres), or via a space link. Either way, ultra-stable optical clocks rather than microwave frequency standards have an important role to play in the future to furthering our understanding of pulsars, and for geodesy.

3. OPTICAL TECHNOLOGY FOR SPACE APPLICATIONS

The time-scale of the required laser stability depends on the space application (or combination of applications). For purely coherent communications, only linewidth is important, i.e., short-term stability over less than a fraction of a second. The DSN frequency source stability-time requirements are generally, (for say Doppler ranging) dominated by the time taken for the electromagnetic radiation to travel across the solar system - typically thousands of seconds. Certain scientific experiments (and other applications) may demand even longer stability timescales. In addition, the absolute value of the frequency source - its accuracy - may become important.

Coherent communications requires narrow lasers with linewidths ranging from sub-Hz to > MHz, depending on the data-rate. Typically, the required linewidth is a few orders of magnitude below the data bit-rate. Two types of cavity can be used for narrowing and stabilisation. Such ultra-stable optical frequency sources are based on two complementary technologies to stabilise the laser radiation: (i) high Finesse ultra-low expansion (ULE) cavities[16], and (ii) cryogenic sapphire dielectric cavity resonators[17,18]. Sub-Hz ULE-stabilised laser linewidths[16] have been observed on Earth, but these may become dominated by vibration at the highest levels of stability. Vibrations can be a serious problem on satellites[19], but it may ultimately prove possible to provide better vibration isolation in space than on Earth.

Whilst the SILEX and GOLD programs are based on direct detection, subsequent ground-based research and development of optical terminals in Europe has focused on coherent systems such as the SROIL and SOLACOS systems mentioned above[4]. The issue of direct detection versus coherent (heterodyne or homodyne) systems for communications has been examined by numerous authors over the past 15 years (see for example, Chan[20]). However, in some situations where power is at a premium, where signal-to-noise is bad or data rates are pushed to their limits (> 1 GHz), coherent

detection becomes attractive. For low-data-rate applications, where only low power levels can be achieved, coherent systems will require state-of-the-art optical frequency sources - linewidths as narrow as 25 Hz have been mentioned for a DSN relay station application for the Pluto Express mission[21].

The Institute for Communications Technology of the German Aerospace Centre (DLR) has developed an "absolute frequency reference at 1064nm for coherent transmission and laser drift measurement"[22]. The doubled (green 532 nm) output is stabilised to the flank of a Doppler-broadened iodine absorption line to 7 MHz (2.5×10^{-8}). Whilst this is modest compared with the ultimate potential of Doppler-free and ion-trap-based optical standards currently being developed[1,16,23], it may be adequate for short-term requirements. It is important to look further ahead and consider more demanding applications. For example, it has been suggested that long-term laser stability of better than one part in 10^{16} over 1000 seconds would be required to provide a performance comparable to that which is projected in the Ka-band for Doppler tracking [12,24], say for the Cassini mission.

Accurate standards will be required for optical frequency space applications, where sub-kHz or even sub-Hz levels may be required. Iodine and other molecular-stabilised lasers can have stabilities of better than parts in 10^{12} at 10 seconds[2]. Recent results in iodine-stabilised Nd:YAG lasers[25,26,27] have been impressive, with stabilities below 10^{-13} for timescales greater than 1 second. However, such molecular-stabilised laser standards are inherently limited by transit-time broadening and second-order Doppler shifts. Such effects may be avoided by using ultra-narrow (less than 1 Hz level) atomic or ionic transitions in species which are trapped and laser-cooled. Laser sources referenced to transitions with natural linewidths close to or below 1 Hz are the basis of the latest generation of optical frequency standards[1,27], and may lead to the development of optical clocks with superior performance compared to existing microwave clocks. To take advantage of such narrow features requires extremely narrow "flywheel" cavity-stabilised lasers, based on the ULE and cryogenic-cavity techniques described above.

Atomic clocks and frequency standards have been an area of intense interest for more than fifty years, with at least an order of magnitude improvement in stability achieved every decade. There is no foreseeable reason why this progress should not continue[28]. An Allan variance analysis shows that the stability of any frequency standard depends on the line $Q = \nu/\Delta\nu$, where ν is the transition frequency and $\Delta\nu$ is the experimentally observed linewidth (limited by interaction time or the natural width). The inherent potential stability of optical (or laser) standards with

frequencies near 10^{15} Hz are superior to those in the microwave (10^{10} Hz), since $\Delta\nu$ is similar in both regions of the electromagnetic spectrum: they are widely expected to become the next generation of ultra-stable accurate frequency sources. Eventually, the timing community could redefine the second in terms of a forbidden optical transition in a trapped-ion[1,16,23]. The principle components of such devices are compact, solid-state, and amenable to space qualification. Some solid-state lasers have withstood Shuttle vibration tests, whilst the space environment is certainly accessible, and offers potential performance benefits.

The wide range of potential space applications demanding stable lasers can probably only be matched by a range of devices and technologies. However, there are significant areas of overlap and already the import of certain common elements has been recognised. Today, diode and other solid-state lasers are most attractive. For example, Nd:YAG lasers (1064 nm) and frequency-doubled Nd:YAG (532 nm) lasers should be able to serve a number of the more demanding application areas mentioned above. Nd:YAG is the laser source proposed for LISA[14], and they are already used in the "SROIL" and "SOLACOS" optical terminals[4]. Also, Nd:YAG lasers are used in satellite laser ranging (SLR) and time-transfer by laser-link (T2L2) experiments. As well as the laser sources themselves, related technologies have to be developed. Pointing, acquisition and tracking capabilities are far more demanding in the optical than the microwave, and there has been much work in the last decade on improving this capability, but together with laser stabilisation, it is one of the most challenging research areas.

4. CONCLUSION

Research in the area of optical sources, frequency standards and clocks is needed to establish the best choices for lasers and associated equipment for future space applications. The demands for optical technology are likely to be applications-driven, starting with narrow-linewidth lasers for commercial (and other) communications. The functions of navigation, tracking and "radio/light science" will push the stabilities and accuracies required from sources. The shift from all-microwave technology to a space-based scenario where optical technology augments microwave technology is already underway: the ultimate system could be all-optical, but that is likely to be well into the next millennium!

***Proceedings of the 13th EFTF AND IFCS, Besançon, (April 1999)**

ACKNOWLEDGEMENTS

CCH, HAK and DJEK would like to thank ESA and the UK NMSPU for supporting studies of optical frequency

control applications at NPL. Discussions with Franco Emma, Stephen Feltham, Mike Geer, Hans Fromm and numerous others are gratefully acknowledged.

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- [24] C. -C. Chen and M. Z. Win "Laser stability requirements for coherent space communications", Proc. 45th Annual Symposium on Frequency Control pp. 500-507 (1991).
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Appendix 6 OHPs from final presentation at ESTEC

ULTRA-STABLE **OPTICAL** **FREQUENCIES FOR** **SPACE**

A study of ultra-stable optical clocks, frequency sources and standards for space applications

ESTEC contract 13290/98/NL/MV

Hugh Klein

**National Physical Laboratory (NPL)
Teddington, Middlesex, United Kingdom TW11 0LW**

**ESTEC Presentation
Noordwijk
16 September 1999**

1. INTRODUCTION

The move from microwave to the optical

2. APPLICATION AREAS OF OPTICAL FREQUENCIES IN SPACE

- Communications
- Navigation, Tracking and T2L2
- "Radio" and "Light" Science

3. OPTICAL TECHNOLOGY FOR SPACE APPLICATIONS

- Incoherent v. Coherent communications
- Gravitational wave detection
- Timing and Deep Space Network

4. STABLE LASER SYSTEMS

- Iodine stabilised lasers
- Optical frequency standards and clocks
- ESA activities

5. CONCLUSIONS

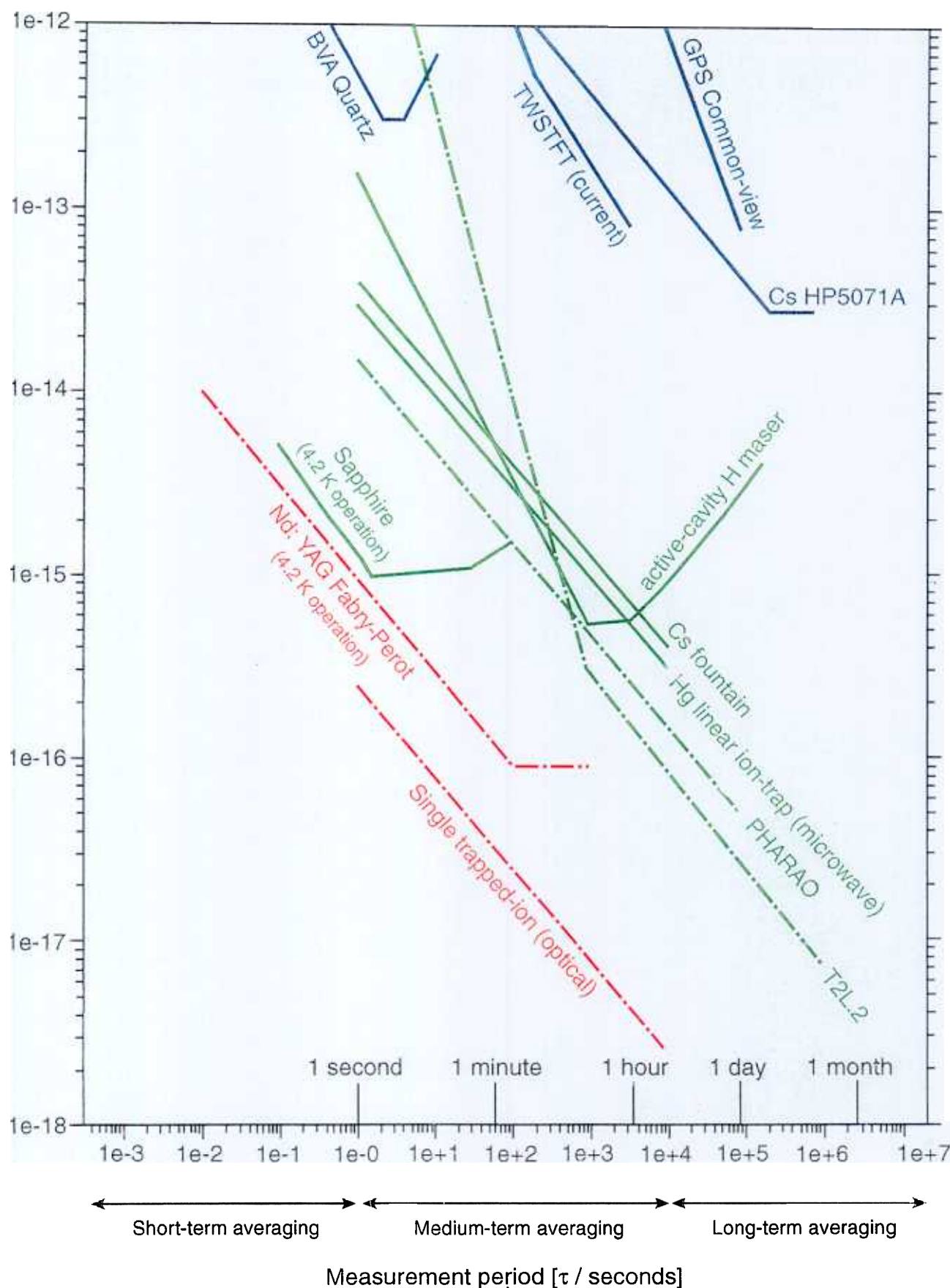
1. INTRODUCTION

The move from the microwave to the optical for space based communications is already underway

- Prospect of vastly increased bandwidth
 - Consideration of optical frequency source requirements.
 - Direct detection systems in first trials
 - Coherent communication offers
> ten times the capacity, but requires spectrally narrow sources
 - but more difficult to implement
- Space Communications 15, pp65-120 (1998)*
- Pointing, acquisition and tracking (PAT) capabilities far more demanding in optical than microwave
 - Optical sources offer higher stability

Allan variance versus measurement period for frequency standards and time-transfer techniques

Fractional frequency stability (Allan variance) $[\sigma_y(2, \tau)]$



Laser-based communication trails - examples

SILEX (Europe)

SPOT-4 (LEO) to ESA Artemis (GEO)
mid-2000 with 50 Mbps planned

GOPEX (US 1993)

Transmission to 6 million km Galileo
space craft from the ground

GOLD (US & Japan)

Ground-to-Orbit Lasercom
Demonstration at 1Mbps
between ETS-VI and
JPL's Table mountain facility in 1996

Locations:

Deep Space, GEO, MEO, LEO,
Aircraft, Balloon, Ground



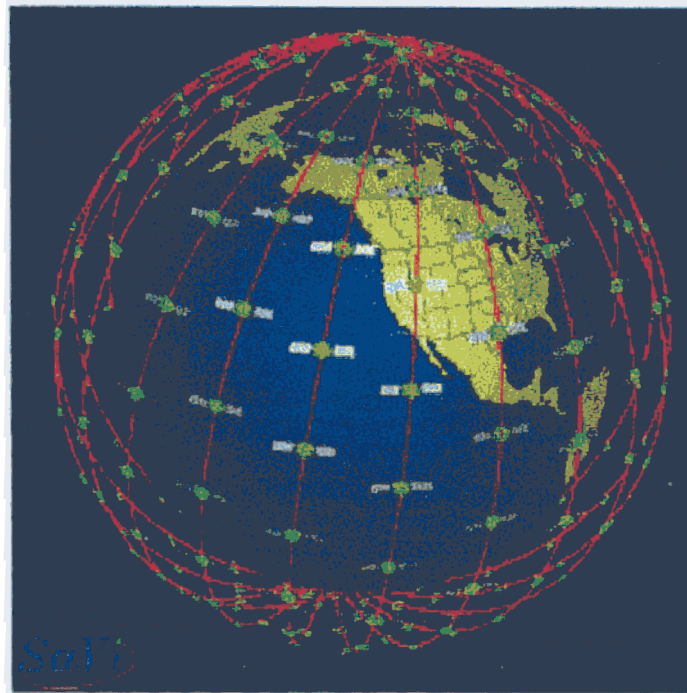
Rotating Earth

TECHNOLOGY

[Visualizations](#)

[Technical Details](#)

[Latency](#)
[White Paper](#)



The Teledesic Network will consist of 288 operational satellites, divided into 12 planes, each with 24 satellites. As the satellite planes orbit north-to-south and south-to-north, the Earth rotates underneath.

2.2 Navigation, Tracking & T2L2

- JPL DSN tracking system frequency specification:

3×10^{-13} at 1000 seconds

"Frequency systems and timing" (1993-1997)

JPL Doc. No D-10145 (15 November 1993)

*DSN source stability-time requirements dominated by time taken by radiation to travel across solar system

- One-and two-way Doppler tracking of the spacecraft signal

** Suggestion that long-term laser stability > 1 in 10^{-16} over 1000 seconds required to provide performance comparable to projected Ka-band Doppler tracking on Cassini

CC Chen and MZ Win, "Laser stability requirements for coherent space communications"

45th Annual Symposium on Frequency Control p500 (1991)

- SLR 2000 mission high-bandwidth real-time Gbps communication links to Mars

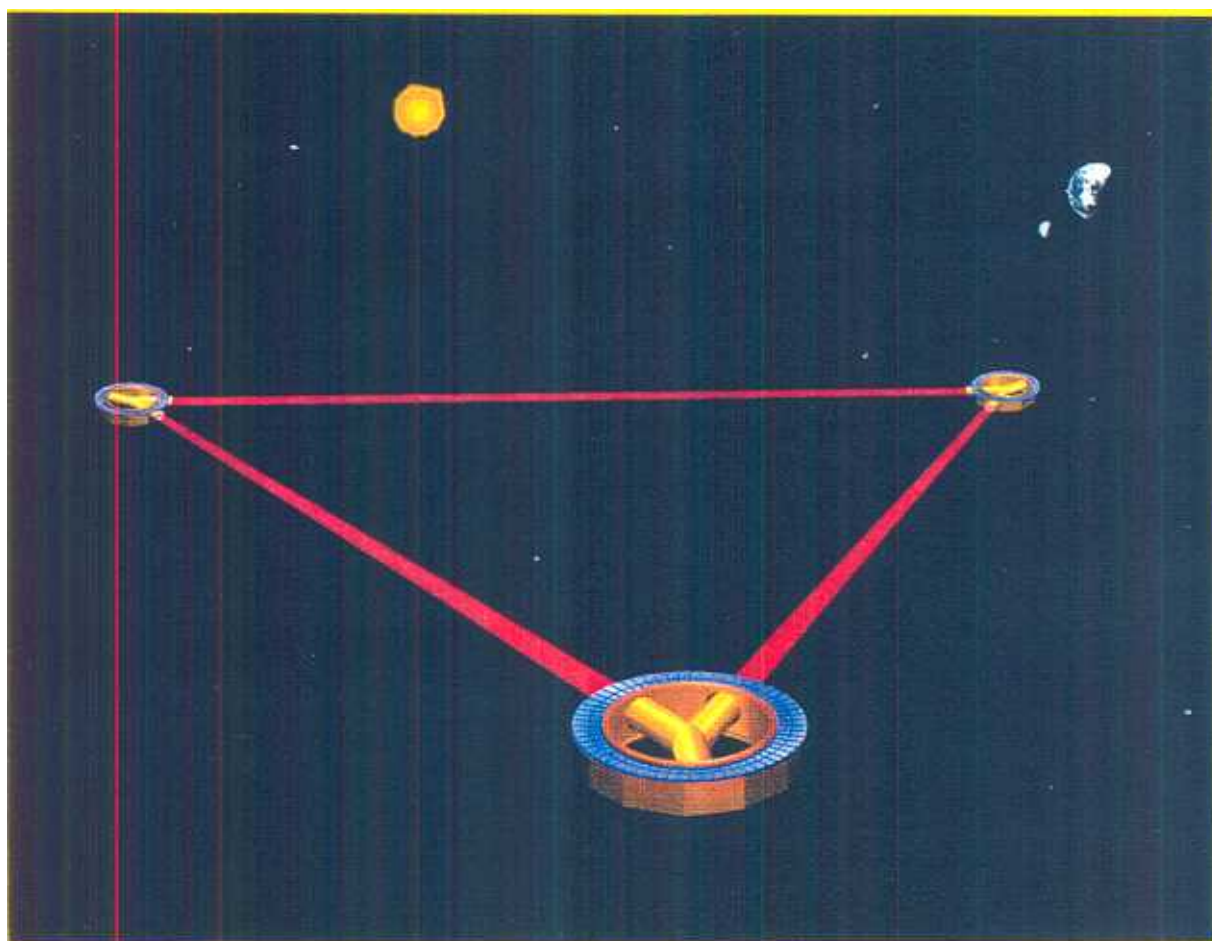
- The MIR-based experiment for ground-based clock intercomparison: relative stability of about 3×10^{-15}

E Samain and P Fridelance Metrologia 35, 155 (1998)

LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

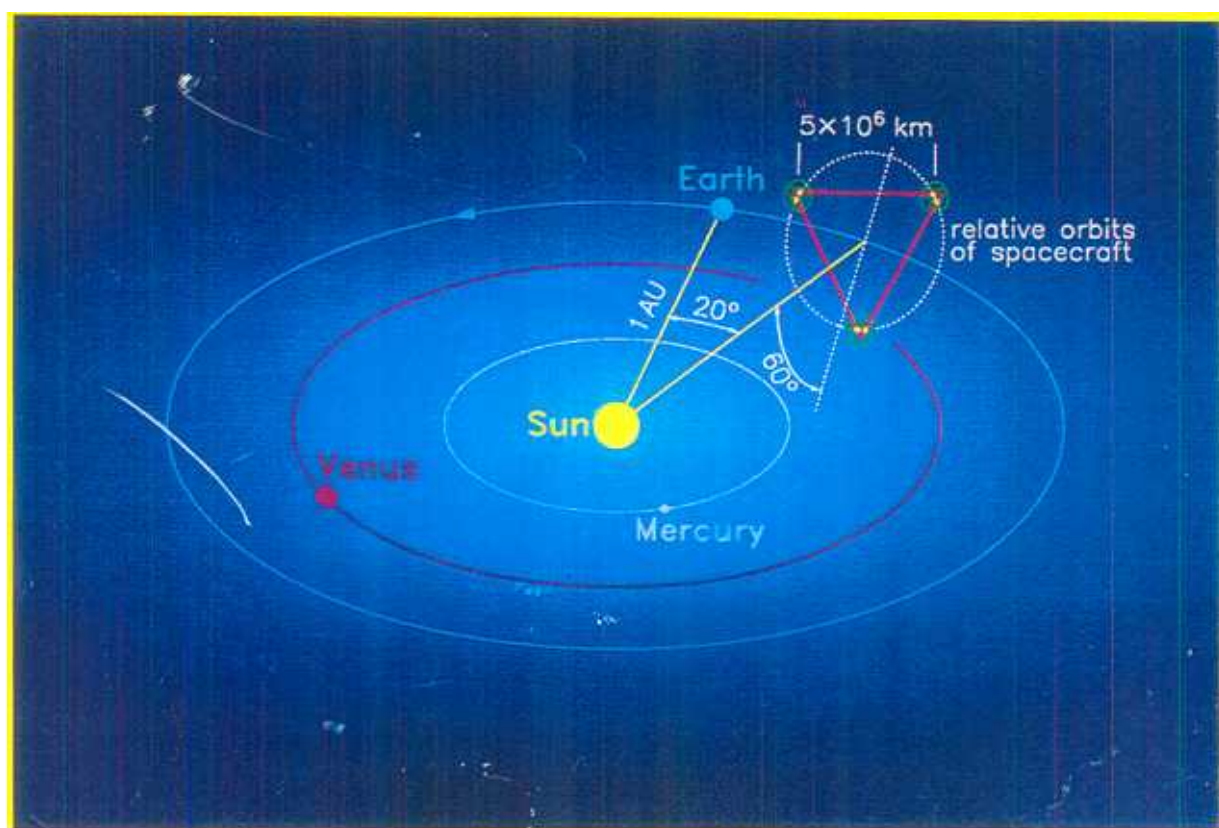
An international project in the field of
Fundamental Physics in Space



Pre-Phase A Report

Second Edition

July 1998



3. OPTICAL TECHNOLOGY FOR SPACE APPLICATIONS

Incoherent communications

- **Hardware does not meet theoretical limit by 10-30 dB**

Reinhard H. Czichy, Space Communications 15, 105-112, (1998)

Coherent communications

- **pure coherent communications requires narrow linewidth**
- **(short-term stability) for $\tau < 1$ sec, linewidth ranges**
- **from sub-Hz to $> \text{MHz}$, and depends on data rate**
- **Linewidth typically few orders of magnitude less than bit-rate**

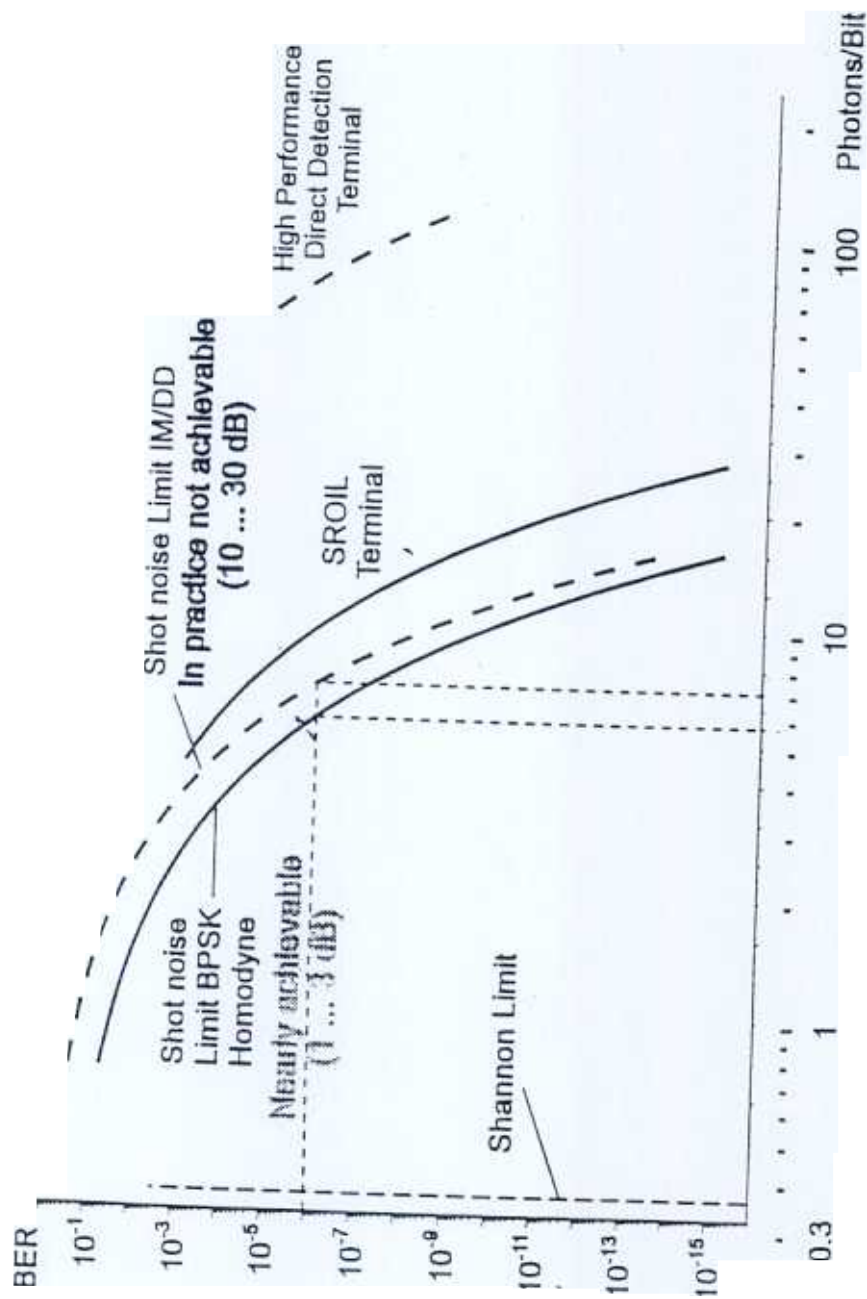


Figure 2 Theoretical sensitivity limits, bit error rate (BER) of coherent and incoherent optical communications systems compared with the practical achievable performance. Taken from Czichy 1998.

Coherent method attractive when:

- power is at a premium
 - signal-to-noise is bad
 - data rates pushed to limit - typically many Gbps
- selected by commercial application

Low data-rate applications may require state-of-the-art optical frequency sources

- linewidths as narrow as 25 Hz mentioned for Deep Space Network (DSN) relay station on Pluto Express

G. Stephen Mecherle et al., "Coherent detection optical relay station satellite for deep-space communication", Proc. SPIE 2123, p.219- (1994)

Trade-off for DSN

- Pulse position modulation versus coherent detection.
- Requirements for space science and navigation may influence system choice.

Gravitational Wave Detection

- **LISA (Large Interferometer in Space Antenna) will require interferometer stabilities of at least 10^{-19} at 1000 to 10,000 sec.**
- **Monolithic nonplanar ring Nd:YAG lasers are planned, locked to ULE cavity to give sub-Hz linewidths.**
- **Increased sensitivity proposed by comparing the mean phase of return light in two interferometer arms with the transmitted light.**

Navigation, Timing and DSN

DSN requirements (presently microwave):

- **Tracking, 3×10^{-13} for 1000 seconds to 12 hour intervals**
- **Radio Science, 1.5×10^{-15} for 1000 to 3600 seconds**
- **VLBI, 10^{-14} for 12 hour intervals**
- **A frequency stability of 10^{-16} is being discussed for the Cassini mission to Mars**

Ultra-stable optical frequency standards may be needed eventually, no firm plans at present

4. STABLE LASER SYSTEMS

Iodine-stabilised Nd:YAG lasers

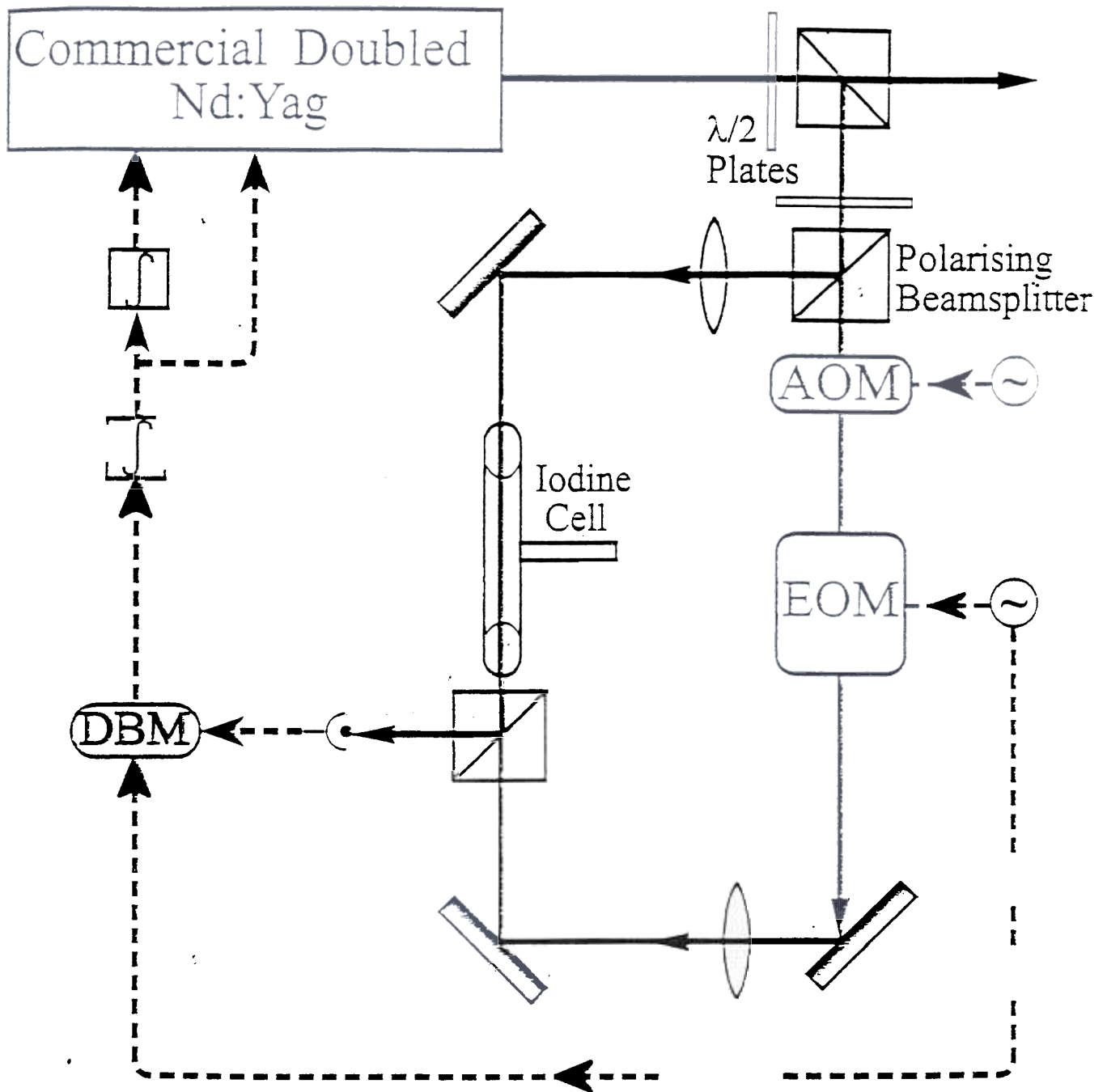
- **Frequency-doubled (green 532 nm)
Nd:YAG output stabilised to flank of
Doppler-broadened iodine absorption line
to 7 MHz (frequency stability 2.3×10^{-8})**

*M. Schulthess and D. Giggenbach, Electronics Letters 34 1854 (1998)
"Absolute frequency reference at 1064nm for coherent transmission
and laser drift measurement"*

- **532 nm iodine-stabilised Nd:YAG lasers
have been impressive with stabilities
below 10^{-13} for $\tau > 1$ sec
*Linewidth transit-time limited***

Two Iodine-stabilised Nd-Yag laser systems at NPL





Schematic diagram of iodine-stabilised Nd:YAG laser

Nd:YAG are in wide use

- **Nd:YAG lasers (1064 nm) and frequency-doubled Nd:YAG (532 nm) lasers, able to serve a number of the more demanding application areas mentioned above**
- **Nd:YAG is the laser source proposed for LISA**
- **Nd:YAG used in the "SROIL" and "SOLACOS" optical terminals**
- **Nd:YAG lasers are used in satellite laser ranging (SLR) and time-transfer by laser link (T2L2) experiments**
- **Narrow free-running starting linewidth of non-planar ring oscillator less than 5 kHz**

Trapped Ions for future optical frequency standards

- **Laser sources locked to transitions with natural linewidth $\leq 1\text{Hz}$, e.g. H and Sr^+ basis of latest generation of optical frequency standards**

Could lead to development of optical clocks with superior performance compared to existing microwave clocks!

Proceedings of the Symposium on Frequency Standards and Metrology ed. James C. Bergquist, World Scientific, (1996), and references therein

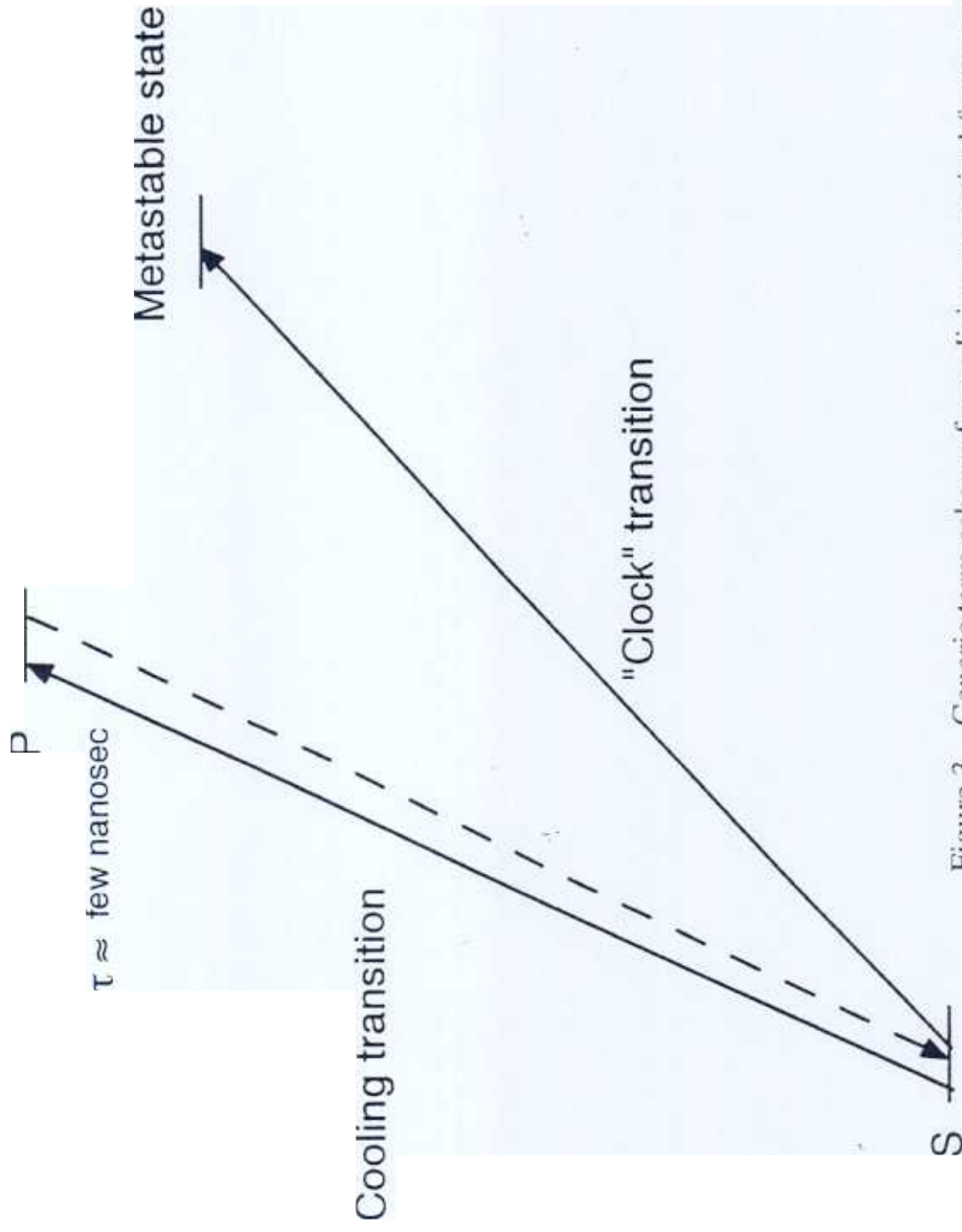


Figure 3 Generic term scheme for realising an optical frequency standard based a single laser-cooled trapped ion (Dehmelt 1975)

Filament
Shield

10 mm

20

Filament

End Caps

Cooling
Laser

Ring

Oven

Compensation
Electrodes

Sr^+
miniature
r.f. trap

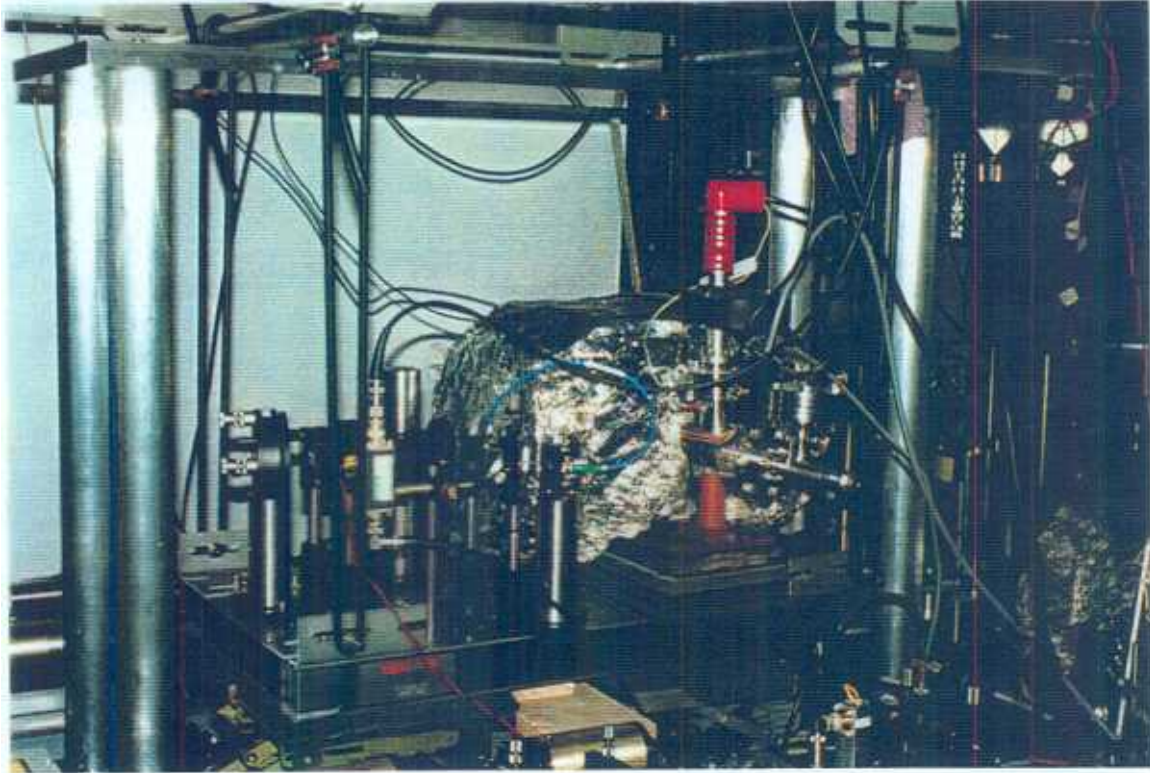
Narrow laser linewidths needed

- To take advantage of narrow features in trapped ions, requires extremely narrow "flywheel" cavity-stabilised lasers, based on ULE and cryogenic cavity techniques
Stefan Seel, et al., PRL, 78, No. 25, pp 4741-4744, (1997).
Farhat Abbas, et al., Proc. 11th EFTF, p. 473, (1997).
- Laser-to-cavity vibration and stabilisation (engineering) issues to resolve

Microwave to Optical Links are needed

- Divider and comb technology development may lead to improved options

Suspended ULE cavity in temperature controlled vacuum system with fibre coupling



Lasers for an Optical Frequency Standard using Trapped Hg^+ Ions¹

Brenton C. Young, Flavio C. Cruz,² Dana J. Berkeland,³ Robert J. Rafac, James C. Bergquist, Wayne M. Itano, and David J. Wineland

National Institute of Standards and Technology, Boulder, Colorado 80303

Abstract. We are developing an optical frequency standard based on the narrow 281.5 nm transition of trapped $^{199}\text{Hg}^+$ ions. A major step toward the completion of this standard is the construction of an isolated high-finesse Fabry-Pérot cavity to stabilize the local oscillator. The cavity system that we have assembled has enabled the creation of an optical frequency source with good short-term stability. Eventually, this frequency source will derive long-term stability from a lock to the Hg^+ transition. We have recently demonstrated an improved linewidth of 0.6 Hz (40 s averaging time) for a 563 nm dye laser locked to our stable cavity. Additionally, we are developing solid-state laser replacements for gas and dye lasers presently used for driving 194 nm and 281.5 nm Hg^+ transitions.

- ¹⁾ Work of the U.S. Government, not subject to U.S. copyright.
²⁾ Present address: Universidade Estadual de Campinas, Campinas, SP, 13083-970, Brazil.
³⁾ Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

CP457, *Trapped Charged Particles and Fundamental Physics*
 edited by Daniel H. E. Dubin and Dieter Schneider
 1999 The American Institute of Physics 1-56396-776-6/99/\$15.00

337

now 0.16 Hz @ 20 sec
~~see also PRL 82 3794 (1999)~~

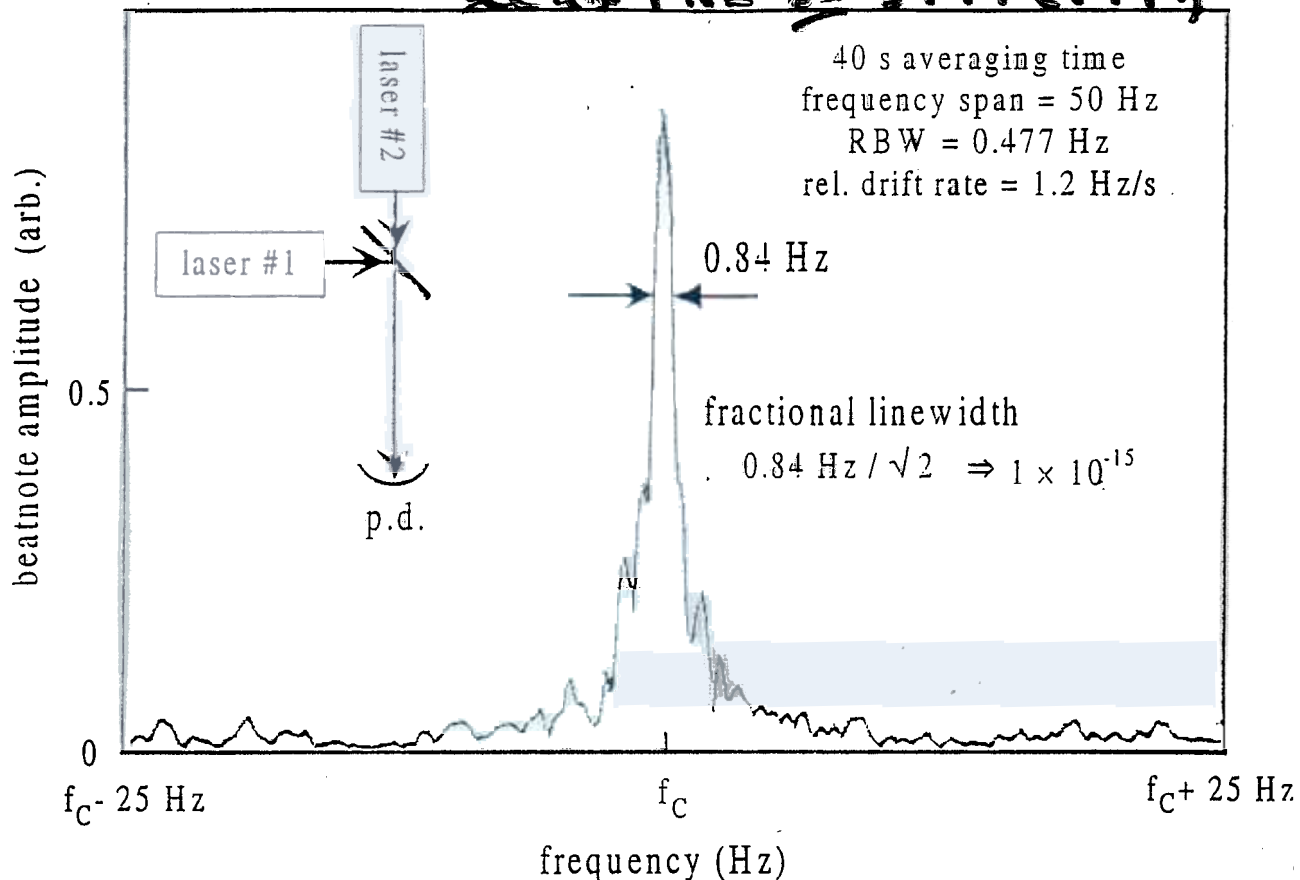


FIGURE 2. Amplitude spectrum of the beat note between two laser beams stabilized to two independent cavities. The dashed line shows the -3 dB level. The averaging time is 40 s. A nearly uniform relative cavity drift of 1.2 Hz/s is suppressed by mixing the beat note with a swept synthesizer.

ESA activities potentially requiring stable lasers

Examples of IITTs:

- **98.1CA.06 Long-range high-speed optical ISL terminals (awarded)**
- **99.1CA.01 High-speed optical networking in broadband satellite constellations**
- **99.1XA.02 Optical ground station for optical data links and Deep Space missions**
- **98.1XA.07 High stability laser for space interferometry (LISA)**
- **98.1XA.12 Core laser technology development**

First two relate to ARTES (Advanced Research in Telecommunication systems) programme, - driven by the high bandwidth requirements of multimedia services.

5. CONCLUSIONS

Coherent Communications

High data rate

- Requirement for absolute standards undefined
- Iodine stabilised Frequency doubled Nd:Yag lasers already demonstrated
- Debate between direct detection and coherent unresolved and commercially sensitive
- Coherent system would require kHz to MHz laser linewidths for commercial systems

Low data rate

- Deep Space Network (DSN) 25 Hz wide laser mooted
- Trade off between pulse position modulation and coherent detection needs to be resolved
- Requirements for navigation and space/light science need to be taken into account

Gravitational Wave detection

- **Very demanding laser stabilities beyond those presently achievable**
- **Sub-Hz wide lasers**
- **Useful to validate laser frequency noise reduction scheme proposed for LISA**

High Stability Timescales

- **Long Term - “optical clocks”**
- **Timescales related to stable optical frequency standards**
- **Potentially higher stability than microwave based scales**
- **Trapped-ion based standards option**

Outlook

- **Currently shifting from all-microwave space-based scenario to optical technology augmenting the microwave**
- **Narrow-linewidth lasers needed for coherent communications**
e.g. multimedia/Internet or DSN
- **Required stability and accuracy of the lasers also depends on additional demands of any navigation, tracking and "radio/light science" functions served**
- **Cavity-stabilised narrow lasers are expected to be the basis of the best laser oscillators for optical space applications eg gravity wave detection**
- **Ultimate systems - all-optical, might also be used for better timescales, but well into the next millennium!**