Microwave Frequency Standards: Tools for Testing the Foundations of Physics in the Laboratory and on Board the International Space Station

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***Abstract*--Two major tasks in fundamental physics are the quantization of gravity and the unification of all interactions. All approaches to achieve these tasks lead to deviations from present day physics. For example, violations of the Einstein's Equivalence Principle are possible. Some violations may manifest as spatial and/or time variations of the fundamental physical constants, and recently attempts to measure these effects have gained considerable attention. One of the most precise tools for testing these theories is the time or frequency standard (clock). This paper discusses the application of microwave frequency standards to testing the foundations of physics. This includes start-of-the-art experiments proposed for both the laboratory and in space. For example, the Atomic Clock Ensemble in Space (ACES) mission, will be launched in 2005 to perform experiments in the micro-gravity environment of the International Space Station. Current plans and future possibilities for Australian participation will be presented.**

Index Terms—Frequency Standard, Atomic clock, Microwave Resonators, Experimental Physics.

INTRODUCTION

THE foundations of Special Relativity (SR) and General Relativity (GR) are based on "Einstein's Equivalence Principle" (EEP)[1]. EEP encompasses the "Weak Equivalence Principle" (WEP) of Newton, which states that inertial mass is equivalent to passive gravitational mass. Einstein added to this by postulating that all the laws of Physics are the same in free-fall and empty space, including electrodynamics etc. As a consequence two more principles were added to EEP, the principles of Local Lorentz Invariance (LLI) and Local Position Invariance (LPI). LLI is tested by local non-gravitational experiments, and essentially checks the validity of the Lorentz Transformation. LPI tests if the influence of gravity is the same for different physical processes situated at the same position in space-time. So far all tests of EEP have confirmed the validity of Relativity to very high precision. On the other hand, models to unify quantum mechanics and relativity lead to possible violations of EEP. Models such as Kaluza Klein and Superstrings require extra dimensions on the order of 10^{-33} cm. Changes in the size of these extra dimensions can lead to changes in fundamental constants. If changes do occur they may occur over the space-time continuum, which necessitates the experimental investigation of both spatial and time dependence of fundamental constants.

Precise measurements are required to test EEP. One of the best tools for precise measurements is the frequency standard, or "modern clock". A modern clock derives time from a well-defined frequency of an electromagnetic oscillator [2]. By searching for small frequency changes a range of tests of EEP may be achieved.

LLI may be tested with frequency standards by performing Michelson Morely (MM) [3-6], Kennedy Thorndike (KT) [7] [5] and one-way speed of light tests[8, 9]. MM experiments test for the spatial variation in the speed of light, c. This is achieved by generating two frequencies that depend on the dimension of a resonator (electronic standard), and are orientated orthogonally. When the experiment is rotated the difference frequency is monitored to test for violations. KT experiments test the velocity dependence of the speed of light. This is achieved by testing a electronic standard against an atomic standard. If violations of SR occur the two standards will be perturbed by the frame velocity in a different way. One-way speed of light experiments test distant frequency standards in motion, and synchronized using slow clock transport. The experiment looks for variations of *c* as a function of the direction of signal transmission. On-way reception and transmission times, to and from the position of both frequency standards must be compared.

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LPI may be tested by determining if two frequency standards based on different physics (such as different atomic species or an electronic standard) couple to the gravitational field in the same way[2, 5, 10, 11]. This may be achieved by testing if the frequency is affected differently as the gravitational potential changes.

Time dependence of the fine structure constant, α, may also be tested by looking for drifts in frequency between two standards. This is because the frequency of different types of oscillators depends on the fine structure constant in different ways.

In this paper we summarize proposed laboratory experiments to implement microwave frequency standards to test EEP. First we detail the tests that will be undertaken at UWA using sapphire frequency standards. Then we detail experiments that will be undertaken in collaboration with French institutes that have developed the world's best atomic standards. Finally we will introduce the Atomic Clock Ensemble in space (ACES) mission. This mission aims to undertake a range of experiments that will test EEP with the aid of a microgravity environment.

Microwave Frequency Standards at UWA

A. *Sapphire Resonator Frequency Standards*

The UWA sapphire frequency standards are based on cylindrical Whispering Gallery (WG) mode dielectric resonators. WG modes are well confined in the sapphire and propagation around the perimeter. The electric energy density is shown in fig. 1. The extremely high quality factor of $5x10^7$ at 77 K (liquid nitrogen) and $5x10^9$ (liquid helium) means that very low noise oscillators may be constructed. However, to create an oscillator with exceptional frequency stability, the resonator must have its frequency-temperature dependence annulled as well as a high quality factor[12]. Unfortunately, the natural Temperature Coefficient of Permittivity (TCP) for sapphire is quite large, around 10-100 ppm/K above 77 K. This mechanism allows temperature fluctuations to transform to resonator frequency fluctuations. Alternatively, an ultra-sensitive temperature control system must be used, which is capable of controlling the temperature fluctuations to a few nK[13].

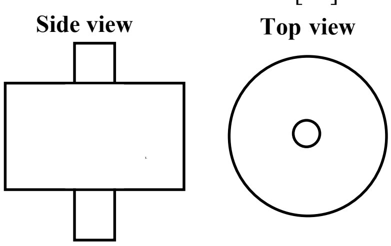

Fig. 1. Energy density in a sapphire dielectric Whispering Gallery mode resonator.

At UWA we have investigated various methods of compensating the TCP of a sapphire dielectric resonator at different temperatures. The usual electromagnetic technique of annulment is due to the effect of paramagnetic impurities providing a compensatory temperature coefficient. This technique has only been realized successfully in liquid helium environments. Compensation was due to impurity ions that were incidentally in the crystal during the manufacturing process. The high-Q combined with TCP compensation has enabled oscillator frequency instability of order 3 parts in 10^{16} to be achieved[14]. It was shown that using such an oscillator as the "fly wheel" for a cesium fountain enabled it to operate at the quantum limit[15]. For space applications the launch of a 4 K device is not impossible, but expensive and difficult. Recently, there has been an effort to dispense with the need for liquid helium and make a compact flywheel oscillator. To achieve the potential of a typical Cs fountain a stability of order 1 part in 10^{14} is required. Currently work is under way to achieve this goal with solid/liquid nitrogen cooled systems. So far this work appears promising and the realization of this goal should not be far off. Fig. 2, shows comparisons of state-of-the-art secondary and primary frequency standards.

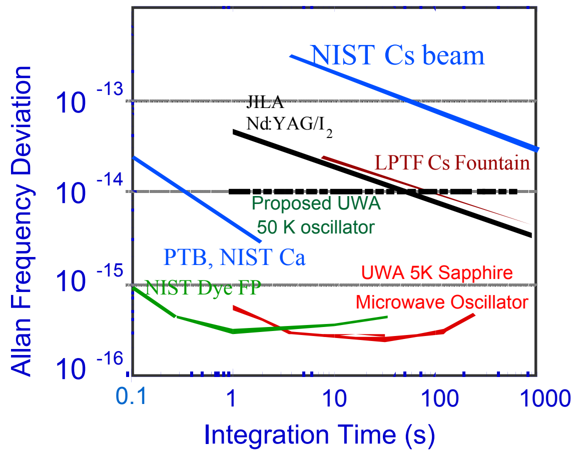

Fig. 2. State of the art frequency standards: Comparison of UWA microwave frequency standards with others worldwide. The UWA sapphire microwave oscillator has the best frequency stability over 3 to 1000 seconds.

In the next section we outline the research program at UWA to develop new frequency standards, to test the foundations of physics. Also, we outline our involvement in testing cold atom clocks such as PHARAO for the ACES mission.

Research Program

A. *Liquid/solid nitrogen cooled systems*

This work aims to develop a secondary frequency standard of 10^{-14} stability for terrestrial and space operation. For space applications liquid helium systems are very expensive, and it would be much better to develop a compact system that can operate at higher temperatures, such as 50 K (solid nitrogen) to 77 K (liquid nitrogen). To meet this requirement two new promising types of frequency standard will be developed: one based on a sapphire-rutile resonator[16]: the other using a sapphire resonator in a dual-mode configuration (patent pending). The sapphire-rutile technique utilizes a small amount of low-loss rutile crystal to compensate the TCP of sapphire, while the dual mode technique utilizes the different Temperature Coefficient of Frequency (TCF) for transverse polarized electric (TE) and magnetic (TM) modes. Transposed gain techniques are then implemented to realise an oscillator based on the difference frequency of the TE and TM modes. Either oscillator could achieve frequency stability of the order 10^{-14} to 10^{-15}. Preliminary design of the resonators has already been made in collaboration with IRCOM[16-18]. The development of such a standard will also have benefits for new-generation terrestrial atomic standards, because of the expense and difficulty of obtaining liquid helium in some locations. Besides the Cs fountain at LPTF, there are at least 15 other fountains under development around the world that will need such a short-term stable frequency standard. The development of these oscillators is vital in the context of the ACES mission and the international effort to search for a drift in the fine structure constant.

If the development of the nitrogen oscillators is successful during 2002, it is possible that one will be transported to CNES in Toulouse for initial tests on the prototype PHARAO during 2002 to 2004. Otherwise, the current plan is to transport a 4 K clock for these tests. This is a much more labor intensive and expensive task. However, under the current French-Australian agreement we have already implemented this process previously.

Recently we have shown that solid nitrogen (about 50 K) has an order of magnitude less temperature fluctuations than liquid nitrogen[19]. Pumping on the liquid nitrogen bath easily creates solid nitrogen. The practicality of operating our standards at this temperature is now under investigation. Preliminary results suggest we can operate the standard at the level of 1 part in 10^{15} frequency instability for the order of a month, without refilling the cryogen. In the space environment it is possible to radiatively cool the system to 50 K, so the solid nitrogen acts as a good test temperature for space operation.

B. *Application of Liquid Helium Cooled Sapphire Oscillators*

During 2000 a 4K UWA sapphire clock was transported to LPTF for a period of at least 4 years. The output of the oscillator will be utilized in a range of experiments on cold atom clocks.

1) Tests with UWA sapphire clock and PHARAO

A test to measure the gravitational redshift on earth will be undertaken in mid 2002. Optical and microwave links between LPTF and the top of the "Tour Montparnase" will be used to transfer the UWA sapphire clock signal to the transportable PHARAO fountain and the stationary fountain at LPTF. The comparison of the two fountain frequencies will be the first terrestrial redshift experiment. This experiment will also act as a test-bed for time transfer at the 10^{-16} level before the actual flight of PHARAO/ACES. Tests will also occur in Toulouse in regards to the ACES mission. The engineering model will be tested for a period of six months in the latter half of 2002, the following year the flight mode will be tested. Both tests will require oscillators from UWA.

2) Quantum tests with cold atom fountain clocks

The scientific goal is to determine the physical limits to the stability and accuracy of microwave cold atom clocks, which we expect at 10^{-16} or below. These limits to the clock performance arise from the fundamental quantum aspects set by the quantum nature of the matter-light interaction (such as the influence of the recoil in the microwave cavity, the effect of the cold collisions, the influence of gravitational Earth potential and its variations). The second goal is to set a limit to the possible drift of the fine structure constant by comparison between Cs and Rb clocks. A double fountain is under final assembly, which will operate simultaneously with Cs and Rb. The goal is 1 part in 10^{16} frequency stability per year or better. In all these experiments, the availability of the sapphire oscillator as an interrogating oscillator is essential.

3) Searching for Anisotropy in the Two-Way Speed of Light

The Superconducting Microwave Oscillator (SUMO) project has been proposed by the Jet Propulsion Laboratory (JPL) and Stanford University[4]. This project proposes to undertake a Michelson Morley (MM) experiment with two independent superconducting cavity stabilized oscillators. The frequency determining elements of the oscillators are orthogonally orientated cylindrical niobium resonators. The beat frequency between the resonators will be monitored as the oscillators rotate around a supposed preferred reference frame. Because of the orthogonality the beat frequency will be modulated with the rotation if any anisotropy exists in the two-way speed of light.

A disadvantage with this technique is that separate microwave oscillators must be configured from the separate cavities. At UWA we have recently proposed the utilization of a single spherical cavity to implement a similar experiment[6]. The modes in a sphere exist in near-degenerate sets, which propagate in different directions on the surface of the sphere. Thus, it is possible to excite modes in a single spherical resonator, which are spatially orthogonal. We believe this offers significant advantages over the SUMO project for the following reasons as considerably more common mode rejection of environmental influences can be expected as the two modes share the same resonator.

4) Test for Drift in Fine Structure Constant with Paramagnetic Doped Sapphire Resonators

A novel method using monolithic Fabry Perot resonators to test for drift in α was recently proposed[20]. The index of refraction of ionic or molecular crystal depends on α^2, thus a drift in α will cause a change in the dispersion characteristic of the crystal. This may be detected by exciting two modes in the same resonator that sample different dispersion. For an isotropic material this may only be achieved at different frequencies. Since sapphire is anisotropic, the dual mode techniques as discussed previously may be implemented to realize a more sensitive version of this experiment. TE and TM modes may be excited at nearly the same frequency, and will sample different values of dispersion. This effect may be amplified with the presence of paramagnetic impurities. Paramagnetic impurities line up in the sapphire lattice in a preferred way resulting in an anisotropic magnetic susceptibility of the lattice. Thus depending on the impurity either the TE (Ti^{3+}) or TM mode (Cr^{3+}, Fe^{3+}) will be largely effected, while the other will not. Thus, if there is a drift in α, a signal will be measurable from the beat frequency of the two modes.

The proposed experiment is to create a 4 K cooled dual mode frequency standard based on a sapphire resonator. The beat frequency will be stabilized and measured. It will be ideal to construct two or more systems. If a drift in α occurs, to distinguish it from a systematic drift comparison with other systems will be necessary.

The Atomic Clock Ensemble in Space Mission

A. Brief Description

The Atomic Clock Ensemble in Space (ACES) is a mission which aims at operating ultrastable clocks on board the International Space Station (ISS). The ACES payload is scheduled to be launched in November 2005 on the UF6 shuttle flight. The ACES payload includes two clocks: 1. PHARAO is a cold cesium atom clock designed by BNM-LPTF, ENS-LKB, LHA with the technical and financial support of the French Space Agency CNES: 2. SHM is an active hydrogen maser designed by ON with a financial support of the European Space Agency ESA. A schematic of the ACES system is shown in fig. 3.

Currently the Australian involvement is with PHARAO, which requires a secondary frequency standard of 10^{-14} stability to probe the atomic transition with quantum limited sensitivity. The Frequency Standards and Metrology (FSM) Research Group at UWA is working in close collaboration with some major scientific research institutes in France, including the French Space Agency (CNES), to build an appropriate secondary frequency standard based on frequency stabilized sapphire microwave oscillators. There are also plans in the future to build a ground station at UWA, which will communicate with the ACES mission to enable frequency standards at UWA to be compared with ACES clocks.

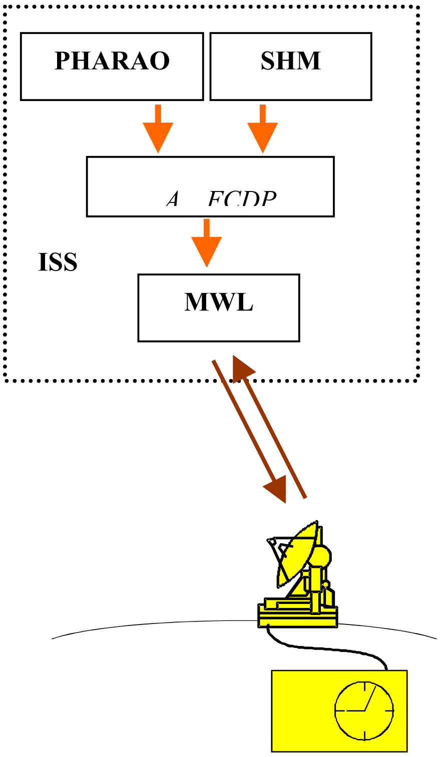

Fig. 3. Schematic of the ACES system.

The PHARAO and SHM clocks can be intercompared on board in the FCDP (Frequency Comparison and Distribution Package). They can also be compared to Earth based clocks using the microwave link MWL (see fig .1). The ACES operation also requires standard equipment such as a payload computer and power distribution unit.

The ACES payload will be installed on a nadir oriented Express Pallet on board the ISS. This pallet will be located either on ISS main truss or on the European pressurized module COLOMBUS. The allocated resources for the complete ACES payload are about 1 m^3 for the volume, 220 kg for the mass and 450 W for the electrical power.

B. Frequency Standards

PHARAO relative <u>frequency stability</u> is expected to be better than $\sigma_y(\tau) = 10^{-13}.\tau^{-1/2}$. This corresponds to frequency stability below 3.10^{-16} for a one-day integration time and below $1.\ 10^{-16}$ for ten days. PHARAO <u>frequency accuracy</u> target is at 10^{-16} level. The SHM relative <u>frequency stability</u> is expected to be:

$$\sigma_y(\tau = 1\ s) \leq 1.5 \times 10^{-13}$$
$$\sigma_y(\tau = 10\ s) \leq 2.1 \times 10^{-14}$$
$$\sigma_y(\tau = 100\ s) \leq 5.1 \times 10^{-15}$$
$$\sigma_y(\tau = 1\ 000\ s) \leq 2.1 \times 10^{-15}$$
$$\sigma_y(\tau = 10\ 000\ s) \leq 1.5 \times 10^{-15}$$

Due to its better medium term stability, the SHM will be used for the evaluation of some frequency shifts affecting PHARAO accuracy and as a high spectral purity local oscillator for PHARAO.

The frequency stability of SHM still is not good enough to operate PHARAO at the quantum projection noise limit[15]. For future missions cryogenic cooled sapphire oscillators are under investigation, which includes nitrogen and helium cooled devices[13, 14, 16].

C. ACES Science Objectives

The first part of ACES mission will be a 6 months characterization phase (evaluation of clocks and T&F links performance). Then, the utilization phase (12 to 30 months duration) will take place. ACES user groups have identified experiments in the following domains:

- physics of cold atoms
- relativistic effects
- precise orbit determination
- laser time transfer
- microwave link
- time and frequency metrology
- geodesy
- earth observation

ACES has obvious objectives in time and frequency metrology (primary standards, clock comparisons, time scales, etc.). ACES tests in Fundamental Physics are of outstanding importance and will be further detailed.

1) Measurement of the Gravitational Frequency Shift

A direct consequence of the equivalence principle, a pillar of Einstein's General Relativity, provides that a source of radiation in a gravitational potential U_s appears to an observer in a different gravitational potential U_o shifted in frequency by an amount $\Delta f/f = -\Delta U/c^2$ where $\Delta U = U_s - U_o$ is the gravitational potential difference between the source « s » and the observer « o » positions. Pound and Rebka made a direct determination of this effect in 1960 using the Mossbauer effect. The result confirmed the prediction of the theory to within 1%. The most precise measurement of this gravitational shift is presently the Gravitational Probe A experiment performed in 1978 by Vessot, Levine and colleagues[21, 22].

The ACES red shift measurement will use a different technique. Instead of modulating the red shift by changing the altitude of satellite, ACES will utilize the high accuracy of the PHARAO clock (10^{-16}) and ground clocks (10^{-16} or better) to make an *absolute* measurement. Knowing precisely the orbital parameters of the space station (position and velocity), the frequency difference between the ground clocks and the PHARAO clock will be calculated and compared to theory. As the ISS orbit changes as a function of the time, the gravitational redshift will also be modulated but only by about 10% of its magnitude.

If both the ground and space clocks used in the frequency comparison possess an accuracy of 10^{-16} and if the link does not degrade clock performance, then the red shift can be determined with a relative uncertainty of 3 parts in 10^6. This represents a factor 25 improvement over the GPA experiment.

2) Search for a Possible Time Variation of the Fine Structure Constant

The fine structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar c$ {equal to 1/137.0359895(61)} characterises the strength of the electromagnetic interaction in an atom or a molecule. In 1937 Dirac suggested that it was interesting to check if these fundamental constants were indeed constant in time and a great deal of effort has been devoted to this goal with increasing precision. In General Relativity as in other metric theories of gravitation, a change in time of non-gravitational constants is forbidden. This is a consequence of the equivalence principle. However, a number of modern theories predict the existence of new interactions, which violates Einstein's equivalence principle. Damour and Polyakov for instance predict a time variation of the fine structure constant[23].

Among the numerous experiments designed to check the equivalence principle, methods utilising space (STEP, MICROSCOPE), and stable clocks have a long history. The high stability and accuracy of the ACES clocks and of the cold atom ground clocks make the search for a drift in α a very attractive proposition. The principle involves the comparison of atomic clock frequencies based on different atoms for long periods of time. Any change of the frequency difference between two clocks might be attributed to a change of fundamental constant or to imperfections in long term behaviour of the clocks. Therefore to make a convincing test, it is mandatory to involve a large number of clocks and to make cross-correlation between the measurements. ACES will provide access to a large number of laboratories worldwide (including Australia). This will involve many different types of clocks, based on cesium, rubidium, hydrogen, mercury ion, ytterbium ion, etc. These frequency standards operate either in the microwave or optical domain.

In the case of an alkali atom with atomic number Z and having a hyperfine transition in the microwave domain, Prestage et. al.[24] calculated the effect of a possible drift of α upon the hyperfine energy as a function of Z. The calculation showed a very rapid variation of $(d\alpha/dt)/\alpha$ as a function of Z (more than quadratic). If one then makes the ratio between the hyperfine energies of two (or more) atoms having very different Z numbers, one finds the sensitivity of the test of the constancy of α. For instance, if $(d\alpha/dt)/\alpha = 1.\ 10^{-14}$/year, then a frequency drift of $1.4\ 10^{-14}$/year would occur between a cesium clock (Z=55) and a mercury ion clock (Z=80). For cesium and rubidium (Z=35) this figure is $0.45\ 10^{-14}$/year. In 1995 Prestage et. al. established an upper limit for $(d\alpha/dt)/\alpha<3.7\ 10^{-14}$/year[24]. Since both the ACES cesium clock and ground rubidium clocks will have 10^{-16} accuracy, the frequency drift can be determined with a resolution as low as $\sqrt{2}.10^{-16}\,/\,year$ giving an improvement of a factor 100 / year. For a 3 year mission the gain is larger than 300. The Z dependence means that the signature of a drift of α, if found, will be unambiguous. Such a discovery would be a major breakthrough and have profound implications on our understanding of the laws of physics. Recent astronomical observations by an Australian group[25] led to a suggestion of a fractional change in the fine structure constant since the early Universe (z>1) of around $2\ 10^{-5}$. However, these results still remain ambiguous, and the ACES mission offers the first unambiguous test by the proposed worldwide consortium.

3) Test of Special Relativity

A number of alternative theories that allow for violations of special relativity have been developed (see ref[1] for a review). These theories all postulate some "universal rest frame" Σ in which the basic postulates of special relativity are valid, in particular, that the slow clock transport and Einstein synchronization (ref[26] pp. 38-40) procedures for distant clocks are equivalent. In special relativity this is also valid in any inertial frame S moving at constant velocity **v** in Σ, however this is not the case in the alternative theories. In this case, the speed is constant for a light signal transmitted one-way between two distant points in Σ (i.e. independent of the direction of signal transmission), but not in S.

For experiments that measure one way signal transmissions, a simple test theory based on a parameter $\delta c/c$ is often used. In this interpretation distant clocks are synchronized in S using slow clock transport. Then c is the round trip speed of light (independent of the chosen synchronization convention) and δc the deviation from c of the speed of light in S (measured by the transport synchronized clocks) for a signal propagating one-way along a particular direction. Then the experiments look for a variation of $\delta c/c$ as a function of the direction of signal transmission in S. In special relativity $\delta c/c = 0$ which, of course, reflects the fact that the two synchronization conventions are equivalent.

A number of experiments testing for a non zero value of $\delta c/c$ have been carried out either by direct measurements of the variation of one way transmission times of light signals between distant clocks or by indirect measurements searching for the variation of the first order Doppler shift. The former used the clocks and time links in the JPL deep space tracking network[8] and the GPS system[9], the latter the first order Doppler effect in Two Photon Absorption[27], the Mössbauer effect[28], and the frequency links of the GP-A experiment[21, 22]. A violation of special relativity is, in this model, linked to a particular spatial direction (velocity $\vec{v}$ of S in Σ) and the experiments search for the modulation of the effect as the direction of signal transmission is changed. Consequently those experiments that rely on the rotation of the Earth for a change of direction are only sensitive to the component of $\delta c/c$ that lies in the equatorial plane.

The ACES experiment is expected to improve previous limits on $\delta c/c$ by about one order of magnitude. The experiment will compare the space clocks to the ground clocks continuously during the passage of ISS. The time transfer link will consist of microwave signals that are exchanged in both directions between the clocks. All emission and reception times and frequencies are measured on the local space and ground clocks respectively. The difference of the measured reception and emission times provides the one-way travel time of the signal plus some unknown but constant offset Δ_s due to the fact that the clocks are not synchronized (by slow clock transport). Then the difference of the up and down travel times is sensitive to a non zero value of $\delta c/c$ along a preferred direction.

$$T_{up} - T_{down} = \Delta_s + \Delta_m + 2\frac{\delta c}{c} T\cos\theta \qquad (1)$$

where T is half the return travel time, θ is the angle between the link and the preferred direction, and Δ_m are known small corrections due to path asymmetries, atmospheric delays, etc. Δ_s is unknown (desynchronization) but remains constant, so adjusting the cosine to the data over the passage allows the measurement of $\delta c/c$.

The sensitivity of the experiment is determined by the instabilities over one passage of both the clocks and T&F links phase. The value of T varies during the passage (min. ≈ 1.5 ms, max. ≈ 8 ms), with an overall time instability over one ISS pass as low as 1 ps, the expected sensitivity to $\delta c/c$ should be in the low 10^{-10} region, which is an improvement by a factor 10 or more over previous measurements. Such a performance seems even more plausible when considering that several systematic error sources (atmospheric delay, orbit accuracy, clock stability) that were likely sources of uncertainty for the GPS experiment[9] will be negligible for ACES. This is because of the two-way systems (cancellations between the up and down links) and the high stability of the ACES clocks.

Summary

In November 2005, the ACES mission will be launched. This mission will include the first space borne cold atom clock, PHARAO. The mission is fully funded by CNES (French Center for Space Research) and has a tight schedule. Australian participation will include the development of probe oscillators to test the clock prior to launch and the development of probe oscillators for future space missions. With appropriate funding it will be possible that Australian developed technology will be space borne. Also, it is intended to build a ground station at UWA Perth, to communicate with ACES as part of a worldwide effort to compare time at different places and with different types of clocks. The prospects to perform test on the founding principles of physics, such as relativity and quantum mechanics are outstanding.

Acknowledgment

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