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PARCS: NASA's laser-cooled atomic clock in space

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Abstract

The Primary Atomic Reference Clock in Space (PARCS) mission is designed to perform certain tests of relativity theory, to study the performance of individual GPS space-vehicle clocks, to study the dynamics of atom motion in microgravity, to advance the state-of-the art for space clocks, and to serve as a pathfinder for precision instruments based on laser cooling of atoms. After a brief overview of the project, this paper discusses the specific objectives of PARCS, describes the key subsystems, and discusses the systematic frequency shifts that limit the accuracy of the clock.

Keywords: Atomic clock; Cesium clock; Frequency standard; Tests of relativity; Laser-cooled clocks

1. Introduction

In the microgravity environment of the International Space Station (ISS), cesium atoms can be launched more slowly through the clock's microwave cavity than on Earth, reducing a number of effects (including systematic effects), thus improving the performance of an atomic clock beyond that achieved on Earth. A more accurate and stable clock in space can be used for a number of purposes including: tests of gravitational theory, study of Global Positioning System (GPS) satellite clocks, study of neutral atoms in microgravity, and more accurate realization of the second, which can then be made available worldwide. In addition, advanced atomic clocks such as Primary Atomic Reference Clock in Space (PARCS) are expected to some day contribute to space exploration (particularly navigation) of the Moon and beyond. PARCS (Jefferts et al., 1999; Heavner et al., 2001) and two other cooled-atom-clock programs, Atomic Clock Ensemble in Space (ACES) (Feltham et al., 1999) and Rubidium Atomic Clock Experiment (RACE) (Fertig et al., 1999) have been scheduled for flight on the ISS, although the Space Shuttle accident has thrown the future of some of these missions into question. In fact, in response to a recent change in NASA's priorities, PARCS and RACE are no longer being developed for flight on the ISS. However, NASA is continuing to fund PARCS as a ground investigation with the hope of identifying other avenues for flight.

2. Specific objectives

For more detail on the specific objectives see Ashby (2001).

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2.1. Gravitational frequency shift

Einstein's theory of general relativity provides very explicit predictions on the behavior of clocks in motion and in varying gravitational potentials. A key objective of PARCS is to test this prediction with a level of uncertainty that is more than an order of magnitude better than previously performed (Vessot and Levine, 1979). While an improved test of this theory on the ISS will not yet allow us to distinguish between the various theories of gravity, subsequent experiments in other orbits (such as a highly elliptic Earth orbit or a close solar probe) should provide more exacting tests of the theory. Such tests are important, because the alternate formulations of general relativity provide differing inputs to cosmological models. Thus, this experiment not only improves upon previous tests, but also serves as a pathfinder for future tests of the theory.

For this measurement, the absolute frequency of the space-borne clock is compared with the frequency of a clock on Earth employing a measurement of the accumulated phase difference (Ashby, 2001) between the two clocks. The measurement of the accumulated phase difference makes best use of the long-term stability of the space-borne clock, since a long time interval is available for the measurement. The best level at which the gravitational frequency shift has been measured is 140 parts in 10^6 in the Gravity Probe A experiment (Vessot and Levine, 1979). With the reasonable assumption that the uncertainty of the frequency of the clock on Earth is 5×10^{-16}, we estimate that the comparison of the total shift will be 40 times better than previous measurements and that removal of the Doppler contribution to this total shift will yield a measurement of the gravitational part of the shift that is 12 times better than that made by Gravity Probe A.

2.2. Kennedy–Thorndike experiment

The Kennedy–Thorndike experiment is the unequal-arm interferometer variation of the well-known Michelson–Morely experiment. Both experiments test the constancy of the speed of light, the very foundation of special relativity. In the clock version of the Kennedy–Thorndike experiment, the laser-cooled cesium clock is compared to a clock with a resonance that is based on the length L of a cavity oscillator (Ashby, 2001). The oscillator chosen for our experiment is the Superconducting Microwave Oscillator, SUMO (Lipa et al., 1999). This latter oscillator is analogous to an arm of an optical interferometer in that the resonance frequency is primarily dependent on the defining dimension of the oscillator as well as the value of the speed of light along that direction. In contrast, the cesium atoms provide a reference that is believed to be stable over time and independent of orientation. As the spacecraft turns, the direction along the length L of the cavity turns, and the frequency of the resonance could be influenced by any spatial anisotropy in the speed of light. The test of relativity then involves a study of the dependences of the frequency of the cavity oscillator on the orientation of L with respect to the oscillator's velocity through an underlying "preferred" reference frame.

The analysis of this experiment is based on Mansouri and Sexl's (1977) relativity test theory. Stability (not accuracy) of the laser-cooled clock for an orbital period (∼5500 s for the ISS) is crucial in performing this test, since this will allow synchronous detection (at the orbital frequency). The best current Kennedy–Thorndike experiment is that made by Wolf et al. (2003). We estimate that the PARCS–SUMO comparison can be performed at least two orders of magnitude more precisely.

2.3. Realization of the second

The key limitation to the uncertainty of the realization of the second is a direct consequence of the limited observation time of atoms in Earth-based cesium frequency standards, that is, gravity simply pulls the atoms out of the apparatus. One result is that the linewidth of the observed transition is broader, limiting the determination of the resonance center. However, the more important effect is that the atoms must move at higher velocities where the Doppler shift and several other velocity-dependent systematic shifts (see Section 4) are larger and more difficult to evaluate. In the microgravity of space, atoms can be launched more slowly increasing the observation time by an order of magnitude and reducing uncertainty in realization of the second by a comparable amount. The projected uncertainty for the PARCS clock is 5×10^{-17}, more than 10 times better than the best current realization (Heavner et al., 2005).

Timekeeping is an international enterprise, and a primary frequency standard (clock) operating on the ISS or any other Earth-orbiting satellite could serve the entire world in a unique manner. Furthermore, the frequency of this space-borne standard could be more easily transferred to various locations on Earth, since it is already becoming difficult to transfer frequency at the current level of accuracy of Earth-based standards. Such transfer could be achieved using either a two-way exchange of laser pulses or the three-frequency microwave transfer introduced by Vessot and Levine (1979) for their test of the equivalence principle. While this experiment has not been planned to last more than six months, we believe that an international cooperation would eventually lead to a more permanent primary frequency standard in space.

2.4. Atom dynamics in microgravity

The microgravity environment of space affords a unique opportunity for studying the dynamics of atom motion, thus testing many of the models that have been developed to describe various aspects of atomic clocks. On Earth, we are limited to a small range of launch velocities, and thus the dynamic range of many of measurements is limited. The greatly enhanced range of possible launch velocities (as low as a few cm/s) should allow us to more clearly observe effects and to test models at levels that cannot readily be approached on Earth. Examples of measurements that could be done better in space include a study of the velocity distribution of atoms within magnetically trapped atom balls (called optical molasses, because of the viscous forces involved) and a more exacting study of the relationship between the number of atoms launched per unit time and clock stability.

2.5. Performance of GPS satellite clocks

Because GPS has become such an important system, extensive studies of the satellite clocks and ephemerides have been done using Earth-based observations. Since the ISS and other satellites are above the troposphere and ionosphere, a PARCS mission affords the opportunity of viewing GPS satellite signals from a decidedly different vantage point. Rather than being limited by the path-delay effects (produced by varying conditions within the ionosphere and troposphere) associated with observations from Earth, observations will be primarily limited by satellite motion and multipath effects associated with signal reflections from adjacent satellite structures. At a minimum, these observations will provide independent verification of what has been learned from the Earth-based measurements, and in conjunction with Earth-based measurements could add to our understanding of the limitations of the system.

The specific measurement that can readily be made with good precision using PARCS as a reference is that of the stability of individual clocks on GPS space vehicles. In this measurement, we single out a given satellite and make a comparison of the stability of the clock on that satellite relative to the PARCS clock. These data are then corrected using the position and velocity data acquired from the GPS receiver that is part of the PARCS package (see Section 3.4) taking the extra precaution of excluding use of the satellite under observation from the GPS navigation solution. This assures that navigation data are independent of clock-comparison data. Since such measurements are made above most of the ionosphere and troposphere and the reference clock has exceptional stability, the stability of the GPS clock can be determined with very high fidelity. The key effects of concern in this measurement are related to multipath effects and the high velocities of the two spacecraft. The Doppler shift is removed to first order by the receiver, and should not pose a significant problem. The multipath effects are of greatest concern, but observation geometries and periods can be readily selected to keep even these to a minimum. In conjunction with simultaneous comparisons made relative to good time scales on the Earth, these data can then be used to enhance the analysis of the performance of individual GPS clocks.

3. PARCS systems

Fig. 1 shows a block diagram of the key space and Earth components. The local oscillator is SUMO. Its output is fed to the low-phase-noise microwave synthesizer, which, under control of the computer, produces frequency offsets steered to the appropriate locations on the cesium spectrum. The synthesizer also delivers a reference signal locked to the cesium resonance frequency to the GPS receiver for common-view comparisons with atomic clocks on earth. Clock control signals, as well as clock and GPS-receiver data, are sent through the relatively low-data-rate communication link shown at the top right of Fig. 1. The accumulated phase difference of the ground and space clocks are compared over long time intervals (many days) with the start and stop times determined by the GPS time-comparison system (see Section 3.4). The resolution of these comparisons is expected to be approximately 200 ps. The GPS receiver also continuously determines

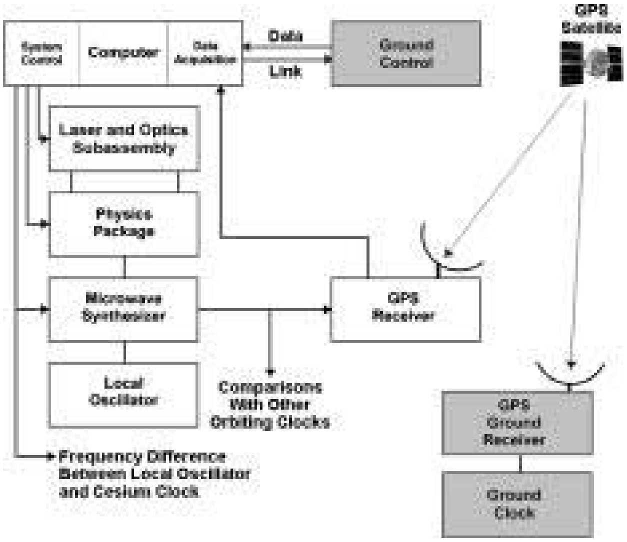

Fig. 1. Block diagram of the PARCS experiment showing the major ISS and ground-station components. The local oscillator is Stanford's Superconducting Microwave Oscillator (SUMO). The ground components are shaded.

both the position and velocity of the clock. These data are needed to correct the frequency comparisons of the ground and space clocks.

We have set a goal for absolute clock uncertainty of 5×10^{-17}, which is 10 times lower than the uncertainty of today's best cesium fountain clocks on Earth. Since the space station is boosted in orbit every one to two months and vibration levels become unacceptably large during such boosts, the plan is to achieve the desired uncertainty in an averaging time τ of 30 days, which requires a clock stability of $8 \times 10^{-14}\tau^{-1/2}$. To achieve this clock stability, we have set a goal of $5 \times 10^{-14}\tau^{-1/2}$ for the stability of the local oscillator. Of course, even this stability would be insufficient without launching more than one ball of cesium atoms at a time into the cavity, since the Dick effect (Dick, 1987) involved in clearing the cavity completely for each subsequent ball launch would result in a stability degradation by at least a factor of two. Launching of several balls during one time period through the cavity structure requires shutters to suppress fluorescence light scattering into the cavity, since such light would produce a frequency shift.

In the following subsections we provide a general description of the PARCS physics package along with brief discussions of clock operation, the atom-beam shutters, and the on-board GPS receiver.

3.1. Cesium physics package

The PARCS cesium physics package (Heavner et al., 2001), shown in Fig. 2, includes a source region where atoms are gathered as optical molasses and launched; a 75-cm long Ramsey microwave cavity (Dick et al., 2003); and a detection region where the states of the arriving atoms are determined using optical methods. A key feature of the PARCS design is the inclusion of three atom-beam shutters (see Fig. 2), which allow optical operations on atoms in the source and detection regions while other atoms are simultaneously in the Ramsey interrogation region. To prevent large frequency shifts, atoms in the interrogation region must be shielded from optical radiation scattered by atoms during state preparation and state detection. The purpose of the shutter and multiple-ball arrangement is to achieve high atom flux at low average density, which reduces the collision shift (see Section 4.1) when running at high stability, as well as to allow nearly continuous atom state interrogation, since clock stability is sharply degraded by dead time.

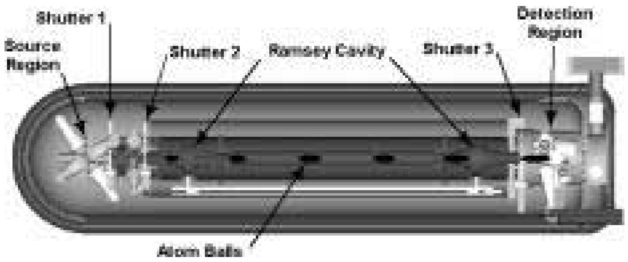

Fig. 2. The physics package for the PARCS atomic clock. The three shutters isolate the Ramsey interrogation region from scattered radiation generated during optical interactions in the source and detection regions. The design calls for launching balls of atoms at a rate that keeps five balls in the cavity at all times. The spacing of these balls is carefully maintained so that the microwave phase can be switched between 0° and 90° between successive balls.

The design goal is to keep five balls of atoms in the Ramsey cavity at all times. In this situation, phase modulation can be very effectively used among other things to eliminate sensitivity to longitudinal vibrations and variations in launch velocity, and to eliminate cavity-clearing times required for frequency modulation. The phase of the microwave excitation can be changed between 0° and 90° after each ball clears its respective cavity end piece. The rapid back-and-forth sampling of the two phase sides of the transition allows us to use a relatively short time constant for the servo loop that locks the local oscillator to the cesium resonance.

The Ramsey cavity consists of two short cylindrical TE_{01} cavities (Ashby et al., 2003) coupled in a symmetrical fashion to the microwave source by a rigid microwave feed. The geometry and dimensions of the TE_{01} end cavities are selected to minimize variations of the amplitude and phase of the microwave field across the 1.5-cm diameter atom-beam channel through each of the cavities. This minimizes frequency shifts produced by atoms sampling different sub-regions of the 1.5-cm aperture.

3.2. Clock operation

Cesium atoms are collected in conventional optical molasses from a diffuse gas of atoms delivered by a conventional atom oven. The atoms are launched with appropriate shifts of the frequencies of the trapping lasers and state preparation is completed by using microwaves to move $m = 0$ atoms from the $F = 4$ ground state to the $F = 3$ ground state. The atoms then traverse the Ramsey cavity where they are subjected to microwave radiation near the cesium frequency of 9,192,631,770 Hz before they enter the detection region where laser fluorescence is used to determine whether the microwaves have induced a transition. To achieve the desired stability, the required number of atoms launched in the $F = 3$ ground in each ball is $\sim 10^6$, which can be readily achieved.

The atom beam shutters are closed to protect atoms in the Ramsey cavity from light scattered when lasers interact with atoms in either the state-preparation region or the state-detection region. The timing of laser pulses and shutter closures are carefully controlled by the system computer. Atoms moving through the clock spread out in both the transverse and axial directions, but those that migrate out from the central axis are stripped off as each ball traverses the clock. The result is that the atom density drops and the ball gradually elongates as it moves through the clock, and the axial extent of the ball entering the state-detection region becomes too great to allow efficient state detection without atom scattering of laser light into the Ramsey cavity. To prevent this, the detection-end shutter slices the elongated ball into multiple pieces with detection being accomplished in each piece before the shutter admits the next piece of the ball. Some atoms are lost in this process, but the number launched in each ball is set to accommodate this loss.

3.3. Atom-beam shutters

The requirements for the atom-beam shutters are extreme, and this has prompted us to design, fabricate and test shutters during early phases of development of PARCS systems. The shutter requirements include: a 1.5-cm clear aperture, light attenuation of more than a factor of 10^6, fast response (<15 ms), long operating life, compatibility with ultra-high vacuum, low vibration, and non-magnetic actuation and materials. The latest design involves a titanium, monolithic, flexure-based mechanism with high motion amplification, driven by a piezoelectric stack. A prototype of this device was constructed and successfully life-tested to 6×10^8 flexures, approximately 3 times the projected lifetime of the experiment. This was a crucial step in the design of PARCS as this was one of the key technologies that carried considerable risk.

3.4. GPS receiver

The GPS receiver for the PARCS mission was developed at the Jet Propulsion Laboratory (JPL) for earlier missions (Duncan et al., 1998; Bertiger et al., 2003). The design has recently been adapted for PARCS (Harris et al., 2003). Along with knowledge of the orbital equations governing the movement of the ISS, this receiver can be used to determine position to 10 cm and velocity to 0.12 mm/s. The concept for time comparisons (time transfer) involves simultaneous, common-view of GPS satellites (Allan et al., 1985) by GPS receivers at the comparison sites in question. Numerous simulations of the time comparisons, using realistic estimates of satellite visibilities from the ISS and scattering of signals from nearby ISS elements (multipath effect), indicate that we can achieve our objective of 200 ps comparisons between the ground clock and the laser-cooled PARCS clock.

4. Systematic frequency shifts

The measurement and control of systematic effects are critical to the success of the mission. These frequency shifts must be well understood, not only to achieve an accurate realization of the second, but also for the gravitational frequency-shift measurement. To achieve the target uncertainty of 5×10^{-17}, all systematic shifts must be known and controlled at a few parts in 10^{17}. We have carefully studied the spin-exchange shift, the second-order Zeeman shift, the black-body radiation shift, the end-to-end cavity phase shift, the second-order Doppler shift, Rabi line pulling, distributed cavity phase shift, cavity pulling, shifts caused by microwave leakage, servo-electronic shifts, and the fluorescent light shift. In the following, we discuss the first four, which are the largest and most important of these shifts. We have found the remaining shifts to be extremely small. Jefferts et al. (2002) provide an extensive discussion of systematic shifts in fountain frequency standards. The discussion of fountain frequency shifts is relevant in almost all respects to the space clock.

4.1. Spin-exchange shift

The spin-exchange shift is caused by collisions among atoms traveling together in the beam and is particularly pronounced when the collision energy is small. The key question is just how the collision shift limits determination of the absolute uncertainty of the cesium resonance. Tiesinga et al. (1992) have calculated this shift for the case of a point source of atoms traversing a cavity wherein the majority of atoms are stripped off at the exit aperture of the cavity, exactly the case for this space clock. For the cesium atomic-fountain clock at NIST, this shift ranges from 4 to 9×10^{-16} (Jefferts et al., 2002). For PARCS, the use of longer Ramsey times as well as the launching of multiple balls significantly reduces this shift below the level of that found in cesium-fountain clocks. Making the simplifying assumption that the shift is energy independent, we have done Monte-Carlo modeling of the shift and find it to be less than 2×10^{-17}. Even if the shift is as large as 5×10^{-17}, we can extrapolate it (by varying the density of the launched balls to well below 3×10^{-17}, so this effect is not expected to limit the accuracy of PARCS.

4.2. Second-order Zeeman shift

This shift arises from the magnetic field imposed on the atoms to assure clear separation of otherwise degenerate magnetic sublevels. For the proposed clock the shift, which scales as the square of the magnetic field, is not large and can be measured with great accuracy. This can be done quite easily by measuring the frequency separation between the ground-state cesium transition ($m = 0 \rightarrow 0$) and the adjacent field-independent transition ($m = 0 \rightarrow 1$) of the Zeeman spectrum.

4.3. Black-body radiation shift

This is an AC Stark shift produced by the black-body background radiation from the enclosure surrounding the atoms. It scales as the fourth power of the absolute temperature, and thus could be dramatically reduced by running the system at a low temperature. This would be difficult and expensive to do in space, and at the level of accuracy of the proposed clock, is not essential. The fractional frequency shift, calculated by Itano et al. (1982), is $\sim 2 \times 10^{-14}$ at a temperature of 40 °C. If the temperature of the physics package is regulated within ±0.1 °C of an accurately measured temperature, the shift can be known and controlled to $\sim 3 \times 10^{-17}$. Such temperature control is not too difficult. The more difficult problem in space is to know the absolute temperature to this level. However, our design studies indicate that this can be accomplished without extraordinary cost. Finally, while the temperature dependence of this effect is well accepted, there is some uncertainty on the magnitude of the coefficient. Several groups are now reworking the theory and performing experiments to more accurately determine this coefficient, and we expect that it will be accurately determined before this experiment goes into space.

4.4. End-to-end cavity phase shift

This shift arises from the residual end-to-end microwave field difference resulting from our inability to machine the cavity end structures to exactly the same dimensions. For conventional atomic-beam standards operating on Earth, the end-to-end cavity phase shift is often determined by reversing the atomic beam, and this could also be done for a space clock. However, a requirement for beam reversal doubles the number of many components and adds complexity that should be avoided. Fortunately, the microgravity environment allows us to launch atoms at widely different velocities, thus providing another means for evaluating this error.

The shift depends linearly on atom velocity, so two points should be sufficient for the extrapolation to zero velocity. Higher velocity launches are preferred, since at low velocity there could be a minor deviation from this linear dependence resulting from variation of the spin-exchange shift with collision energy. At our selected points, 5 and 15 m/s, such variation is estimated to be negligible. Our projected uncertainty for the determination of this shift is a fractional frequency shift of $<10^{-17}$. Despite the fact that only two points are needed for the extrapolation, we expect to add at least one other point, so that we can verify that the effect is linear.

5. Discussion and conclusions

PARCS has successfully completed two major reviews by external panels of experts. These panels studied both the scientific objectives and technical feasibility of the program, and reported favorably on both. The cancellation of the program, along with the entire NASA Fundamental Physics Program, was not based on scientific and technical review, but rather on the practical problems of getting the mission into space following the shuttle disaster. NASA is continuing a lower level of funding for PARCS with the aim of identifying other possible avenues to flight and other applications of the clock technology.

The highest risk aspects of the program have been carefully investigated, and there now appear to be no technical obstacles to flight. The highest risk component, the atom-beam shutter, was developed and a prototype was successfully tested to three times the life of the mission. The level of technology required to achieve the stability goal of $5 \times 10^{-14}\tau^{-1/2}$ was found to be well within the state of the art currently achieved on Earth, and we have found no obstacles to achieving this performance in space. We have carefully studied each of the clocks systematic effects and believe that none poses a substantial challenge. We plan to continue to study the spin-exchange shift, since the energy dependence of this shift for low-energy collisions is not fully understood. However, we believe that our use of very low densities makes this shift extremely small, and that we can readily limit the uncertainty introduced by it.

Our selection of operating parameters has been based on our objective of achieving a substantial improvement over ground-based clocks. In choosing these parameters, we concluded that we could not hope to improve clock accuracy by an order of magnitude in space by use of a set of design parameters that are no better than those used on Earth. In fact, using current fountain-clock parameters (quartz as the local oscillator and no shutters), it would not be possible to even match the performance of ground-based fountains. This is because space clocks must deal with the additional end-to-end cavity phase shift, which does not exist in fountain clocks on Earth.

In summary, the PARCS objectives continue to be compelling, and the value of putting such a system into space is motivating continued study of other flight possibilities.

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