PARCS - A Primary Atomic Reference Clock in Space

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Abstract

NIST, in collaboration with the Jet Propulsion Laboratories (JPL), the University of Colorado, Politecnico di Torino and Harvard Smithsonian Center for Astrophysics (SAO) is building a laser-cooled cesium (Cs) atomic clock for flight on the International Space Station (ISS). The clock, named PARCS (Primary Atomic Reference Clock in Space) takes advantage of the microgravity environment of the ISS to achieve a high stability of $\bullet_y(\bullet) \bullet 5\times10^{-14}\bullet^{-1/2}$ and an ultimate accuracy of $\bullet\ 5\times10^{-17}$, more than an order of magnitude better than terrestrial Cs fountains. Additionally, this accurate clock on the ISS will be used to perform a variety of tests of fundamental physics, such as relativity theory. Since the ISS orbit will cover a large portion of the earth, PARCS will serve as an internationally accessible primary standard thus improving comparisons between international standards laboratories. Here we describe the scientific objectives of the PARCS mission, present our design considerations and laboratory studies of prototypes of clock components, and evaluate the anticipated performance of PARCS such as systematic shifts and the ultimate accuracy of the device.

Introduction

Several primary standards laboratories around the world presently operate Cs atomic fountains with accuracies of $\bullet\ 10^{-15}$ [1,2]. This high accuracy is achieved in part because fountains enable Ramsey times, T_R, of $\bullet$ 1s. However, to increase the Ramsey time by a factor of 10 would require a fountain structure $\bullet$ 100 m high, which becomes experimentally impractical. With a clock in orbit taking advantage of the microgravity environment, it is possible to achieve Ramsey times of $\bullet$ 10 s, thus opening up a new realm of clock performance[3,4]. We anticipate that PARCS can achieve a stability of $\bullet_y(\bullet) \bullet 5\times10^{-14}\bullet^{-1/2}$ and ultimate accuracy of $\bullet\ 5\times10^{-17}$.

A more accurate and stable clock in space will be used for several purposes including: tests of gravitational theory, study of GPS satellite clocks, investigating the properties of neutral atoms in microgravity, and a more accurate realization of the second, which can then be made available to standards laboratories around the world.

Several relativistic effects on clocks will be measured using PARCS. Significant measurements include the gravitational frequency shift, which can be determined nearly two orders of magnitude more accurately than existing measurements, and local position invariance, which can be tested more than three orders of magnitude more accurately than the best current experiments on earth. Should this experiment fly concurrently with SUMO (Superconducting Microwave Oscillator), which is also scheduled to fly on the ISS, local position invariance can be tested more than four orders of magnitude better than current experiments and a Kennedy-Thorndike test can be done five orders of magnitude better than the most accurate experiments on earth. Finally, the realization of the second in space can be achieved with an uncertainty of • 5 × 10^{-17}, a factor of 20 better than presently achieved on earth.

PARCS Overview

As shown in Fig. 1, the experiment is projected to be located on a forward section of the Japanese Experimental Module (JEM) External Facility (EF). This location provides reasonable zenith and nadir views, which are important for time transfer using the GPS constellation of satellites. Furthermore, the available power (3 kW), closed-fluid cooling (2 kW), and volume (1.8 m × 1.0 m × 0.8 m) are well suited to the experimental requirements.

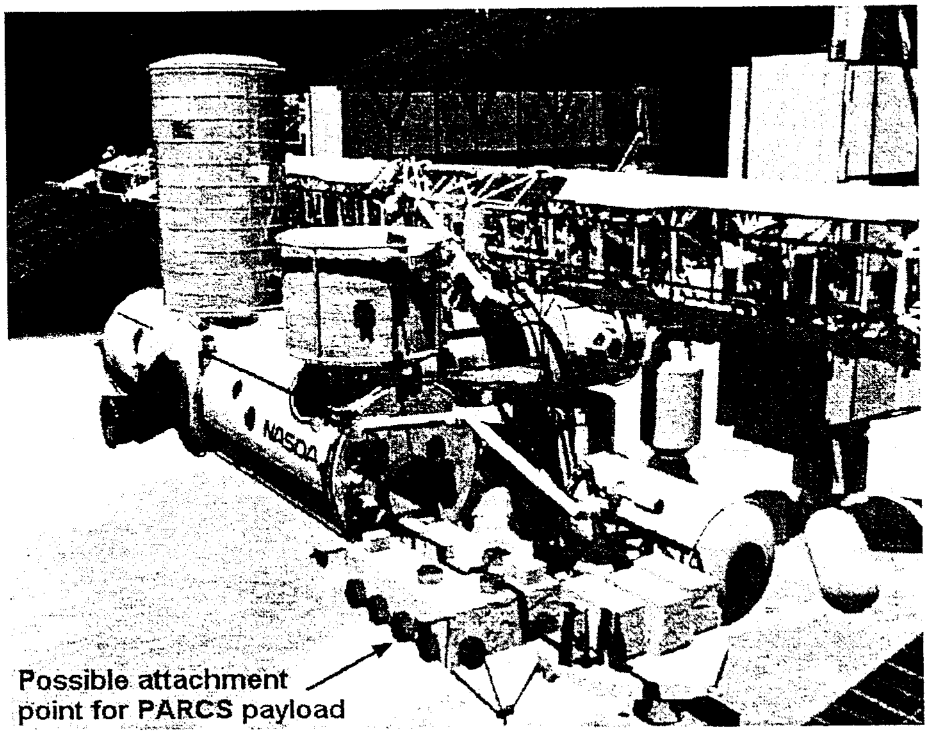


Figure 1. Projected location of PARCS on the ISS.

Figure 2 shows a block diagram of the main space and earth components. The output of the local oscillator, a space-qualified hydrogen maser developed at SAO (Harvard Smithsonian Center for Astrophysics), is fed to the low-phase-noise microwave synthesizer. The output of the synthesizer is then steered under computer control to interrogate the central fringe of the Cs clock transition. The synthesizer also delivers a reference signal at the Cs clock frequency to the GPS receiver for common-view comparisons with atomic clocks on earth. The GPS common-view method is described below. Clock control signals, as well as clock and GPS receiver data, are sent through the communication link shown at the top right of Fig. 2.

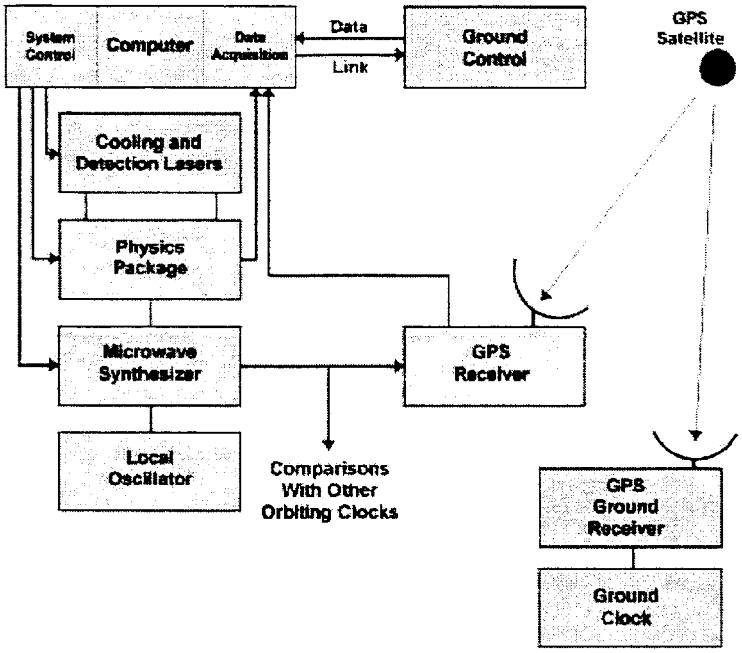
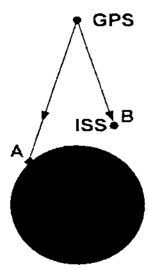


Figure 2. Block diagram of the PARCS experiment showing the major ISS and ground-station components.

Transfer of time and frequency are accomplished using reception of the GPS carrier (phase) in a common-view method shown schematically in Fig. 3. Receivers at point A (an earth ground station) and point B (on the ISS) receive the same signal from one individual GPS satellite. The data acquired at each location is the difference between the reference clock at that location and the GPS clock, with an added signal-transit delay. In differencing the data sets acquired at the two points, the GPS clock cancels yielding the difference, A-B, between the two clock readings, plus the differential transit delay. The delay term has some common-mode components. Using ionospheric-delay data obtained from dual frequency GPS measurements and tropospheric delay estimates, the difference term can be estimated quite well. Dramatic improvement over single observations can be obtained by averaging additional clock differences using all available GPS satellites within common view of the two observing stations. The best result for measurements of this type (for two earth stations) has been an RMS time noise of 30 ps.



$$\begin{array}{c} [\text{A- GPS} -\tau_A] \\ -[\text{B - GPS} -\tau_B] \\ \hline \text{A -B} - (\tau_A-\tau_B) \end{array}$$

Figure 3. GPS common-view method. Signals received at A and B produce the clock differences shown in the first two lines, and the difference between these data removes the GPS reference time as shown.

Figure 4 shows the limitations imposed by the time transfer with both 10 ps and 50 ps stability. For the time-transfer-system limits alone, the two curves would continue downward, but measurements are ultimately limited by uncertainties in the positions of the ISS. The flattening of the time-transfer curves represents a positional uncertainty of 10 cm. The stability of the Cs clock is shown as the straight line below the time transfer curves. The averaging times required to reach particular points on the curve are shown. Figure 4 clearly illustrates that the time transfer system is going to limit comparisons between the PARCS clock and clocks on earth. At the selected stability of • $_y$(•) = 5 × 10^{-14}, time transfer is the limiting factor.

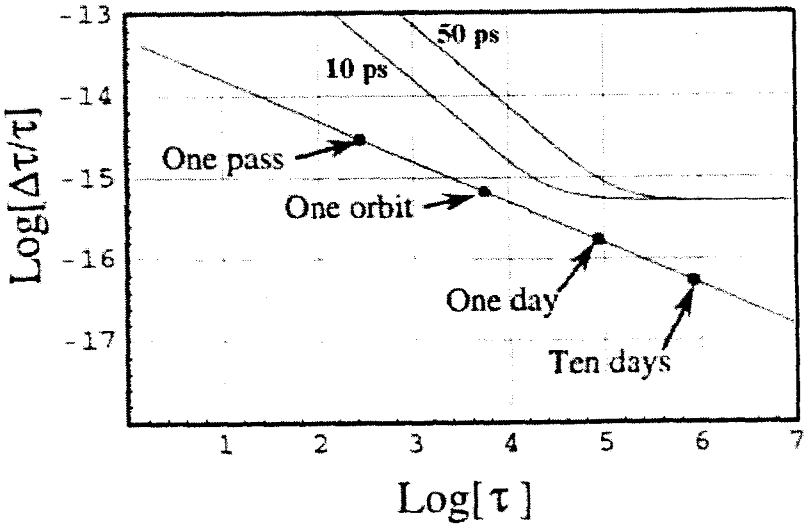


Figure 4. Stability as a function of averaging time • for both the time-transfer system and the PARCS clock. Some specific averaging times are shown on the clock stability. The flattening of the time-transfer curves results from uncertainty in the location of the ISS.

PARCS Physics Package

Figure 5 is an approximate scale diagram of the proposed PARCS physics package. Atoms are collected and cooled to • 2 • K in an optical molasses, (1,1,1) geometry, in the region shown on the left. Launching from the cold atom source region into the microwave interrogation region is accomplished using a moving molasses. A launched ball of cold atoms enters a state-selection microwave cavity which transfers atoms from •F=4,m_F=0 • into •F=3, m_F=0•. The atoms then pass through a shutter and into the Ramsey microwave region which consists of two TE_{011} cylindrical cavities separated by 75 cm. Upon exiting the second cavity, the atoms pass through a second shutter and enter the detection region where the number of atoms in both •F=4• and •F=3• is measured. A normalized transition probability is then calculated and used by the computer control servo to steer the microwave synthesizer. This clock geometry is similar to a conventional thermal atomic-beam clock on earth except that the Cs atoms are much colder and are launched as a sequence of balls. The shutters at both the launch and detection ends are closed while the optical molasses is loading atoms and launching. This is necessary because any resonant laser light scattered into the microwave interrogation region causes large frequency shifts.

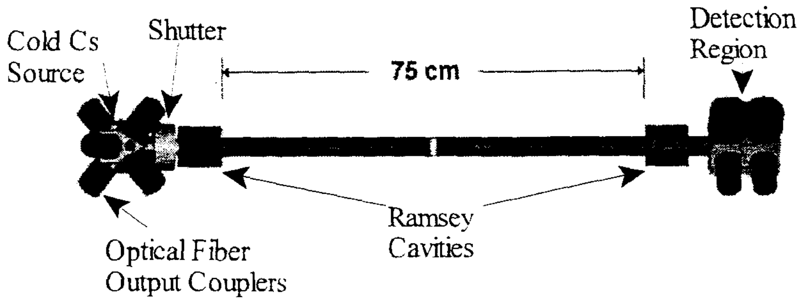


Figure 5. Approximate scale diagram of the proposed PARCS physics package.

Laser light for the optical molasses and detection regions will be delivered to the physics package using fiber optical cables from a separate optics package.

There are different methods with which to interrogate the central Ramsey fringe. One is to operate the clock on one side of the central fringe, and then move the frequency of the synthesizer to the opposite side of the fringe. The difference between the transition probabilities from both sides of the resonance can be fed into a digital servo which adjusts the synthesizer frequency such that the transition probabilities are ½ on both sides of the central fringe. In this case, it is desirable to launch a large number of balls on one side of the line before moving the frequency of the synthesizer to the other side of the line. This helps to minimize degradation of the clock stability due to measurement dead time (Dick effect). Nevertheless, moving the frequency of the synthesizer from one side of the line to the other and performing a servo controlled frequency steer results in a • 10 s dead time while the atoms clear the Ramsey cavity.

The second method of Ramsey interrogation involves independent phase modulation of the two Ramsey regions. In this approach, the two cavity-ends are operated at a phase difference of 90° to produce a dispersion-like response rather than a peak resonance. By inverting the phase of the far-end cavity (closest to the detection region) by 180°, a second, inverted dispersion curve is generated. The intersection of the two curves is a measure of the center of the resonance. The amplitudes of the signals derived from the dispersion curves are driven by the servo system to be equal. While this concept is not new, it has not been implemented in a modern beam clock due to difficulty in accurately maintaining the 90° difference between the two Ramsey cavities. We believe that with modern DDS (Direct Digital Synthesis) synthesizers and advanced microwave techniques, this method is feasible. An advantage of this method is that it is first-order insensitive to vibrations since the system locks on resonance rather than on the sides of the resonance. This is important considering the vibration environment aboard the ISS. A second advantage of this method, as illustrated in Fig. 6, is that the required number of atoms reaching the detection region is reduced for a given stability since the duty cycle is higher than in the frequency modulation scheme. When changing the phase of the oscillator to interrogate the resonance, the resulting dead time is the Rabi time (• 1 s), that is, the time for an atom ball to travel through an individual cavity. However, a servo controlled frequency steer of the synthesizer still results in a • 10 s dead time as in the frequency modulation case. Still, the overall dead time is reduced. This reduced atom number requirement reduces the spin exchange shift. This phase modulation method has been tested on the NIST-F1 cesium fountain and the location of the center of the resonance did not change on the order of 1×10^{-15} compared with the standard frequency modulation scheme.

Systematic Frequency Shifts

Systematic frequency shifts must be well understood, not only to achieve an accurate realization of the second, but also to assure long-term stability for tests of gravitational theory. For an overall frequency uncertainty of 5×10^{-17}, all systematic shifts must be known and controlled at levels of a few parts in 10^{17}. Anticipated systematic shifts in PARCS have been discussed in detail previously [3] and include: the second-order Zeeman shift, the spin-exchange shift, the second-order Doppler shift, the black-body radiation shift, end-to-end cavity phase shift, distributed cavity phase shift, Rabi line pulling, cavity pulling, microwave leakage, servo-electronics shifts, and the fluorescent light shift. We estimate that all of these systematic shifts can be controlled to yield a total uncertainty of • 5×10^{-17}.

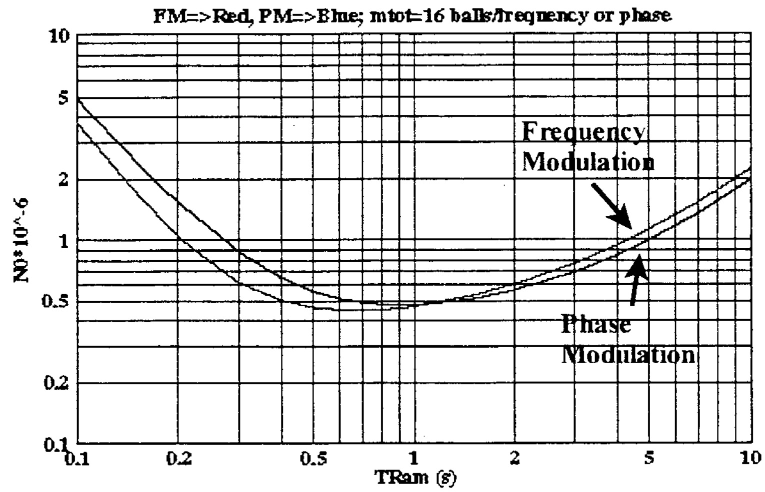


Figure 6. The result of a clock performance model comparing frequency modulation and phase modulation interrogation schemes. The plot shows the number of atoms in the m=0 state needed in each launched ball as a function of Ramsey time for a clock stability of 5×10^{-14}•$^{-1/2}$ using 16 balls per lineside. The phase modulation scheme has a higher duty cycle resulting in lower required atom flux compared to the frequency modulation scheme.

The spin-exchange shift is especially problematic in both PARCS as well as Cs fountains because of the uncertainty in the coefficient as well as incomplete theoretical models. This effect will be the largest contributor in the error budget. However, in PARCS, the use of longer Ramsey times as well as the launching of multiple balls significantly reduces the spin-exchange shift. For a given stability requirement, it is clear that the use of multiple balls reduces the required density for each ball, thus reducing the shift. The reasons why longer Ramsey times reduce the shift are more involved. The clock stability is related to the Ramsey time, T_R, and the number of detected atoms, N_D, by •$_y$(•)• $(T_R N_D^{1/2})^{-1}$. So, as the Ramsey time increases the number of atoms required at the detection region to reach a given stability falls off even faster thus reducing the spin exchange shift.

Prototype Development

A number of components have been designed and fabricated in prototype form. The shutters, which are critical to operation of the PARCS clock, have recently been fabricated, and preliminary testing of them has begun. The shutters must not significantly perturb the magnetic field within the clock nor excessively vibrate the physics package. Also, they must have an open aperture of 1.0 cm, operate at a rate of at least 10 Hz, and survive ~ 2×10^8 actuations.

We have built a laboratory prototype of the cold Cs source and characterized its properties under various operating conditions and determined that we can meet the atom flux requirements to reach our target stability at • 10 s Ramsey times. We are continuing to investigate source operating parameters and anticipate still larger atom flux numbers can be readily achieved. A second generation Cs source with fiber optic cable collimators has been constructed from titanium and will be assembled over the next few months.

A microwave synthesizer with a performance well beyond that needed for PARCS has been constructed, and measurements of phase stability confirm that it meets the required performance. A second synthesizer, incorporating features that better match it to PARCS, and that uses a number of space-qualified components, is nearing completion.

Preliminary designs for the laser system have been produced using, as much as possible, commercially available components. Some components have already been evaluated for vibration immunity. A laser-welding system will be used to assemble a number of the components requiring precise alignment. A jig for achieving correct alignment before welding has been constructed.

The design of a prototype microwave cavity is now complete, and fabrication of the cavity will begin soon.

Conclusions

The PARCS project will use a laser-cooled Cs clock in the microgravity environment of the ISS to perform a variety of tests of fundamental physics as well as to provide a more accurate realization of the second that will be accessible to standards laboratories around the world. The microgravity environment allows for long Ramsey times of T_R• 10 s which results in narrow resonances as well as a reduction in the spin exchange shift (compared with a fountain operating at the same stability). We discussed the basic design goals including a novel phase modulation interrogation that increases the duty cycle of the clock. Many key elements of the system are being prototyped and evaluated.

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