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A U.S. Laser-Cooled Atomic-Clock System for Space*

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Abstract

This paper describes progress toward development of a Primary Atomic Reference Clock in Space (PARCS) and reviews scientific and technical objectives of the PARCS mission. PARCS is a NASA-funded, collaborative effort involving the National Institute of Standards and Technology, the University of Colorado, the Jet Propulsion Laboratory, the Harvard Smithsonian Center for Astrophysics, and Politecnico di Torino. The experiment involves a laser-cooled cesium atomic clock, a Global Positioning System (GPS) time-transfer system, and a hydrogen maser that serves as both a local oscillator for the cesium clock and a reference against which tests of gravitational theory can be made.

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, reducing a number of effects (including systematic effects), thus improving the performance of an atomic clock well beyond that achieved on earth. A more accurate and stable clock in space can be used for several purposes including: tests of gravitational theory, study of GPS satellite clocks, study of neutral atoms in microgravity, and more-accurate realization of the second, which can then be made available worldwide. PARCS [1,2] and two other cooled-atom-clock programs, Atomic Clock Ensemble in Space (ACES) [3] and Rubidium Atomic Clock Experiment (RACE) [4] are also scheduled for flight on the International Space Station (ISS).

Several relativistic effects on clocks will be measured in this experiment. Significant measurements include the gravitational frequency shift, which can be determined about 40 times better than was done previously, and local position invariance, which can be tested to about 120 times better than the best current experiments on earth. Should this experiment fly concurrently with SUMO (Superconducting Microwave Oscillator) [5], which is also scheduled to fly on the ISS, local position invariance could be tested about three orders of magnitude better than current experiments, and a Kennedy-Thorndike test could be done nearly five orders of magnitude better than the most accurate experiments done on earth. Finally, the realization of the second in space can be achieved at an uncertainty of 5×10^{-17}, a factor of 20 better than that achieved on earth.

PARCS completed its Science Concept Review in January 1999 and its Requirements Design Review in December of 2000. Preliminary designs of many components are nearing completion and a number of prototype components have been developed and are being tested. PARCS is currently scheduled to fly in early 2005.

2. System Design

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

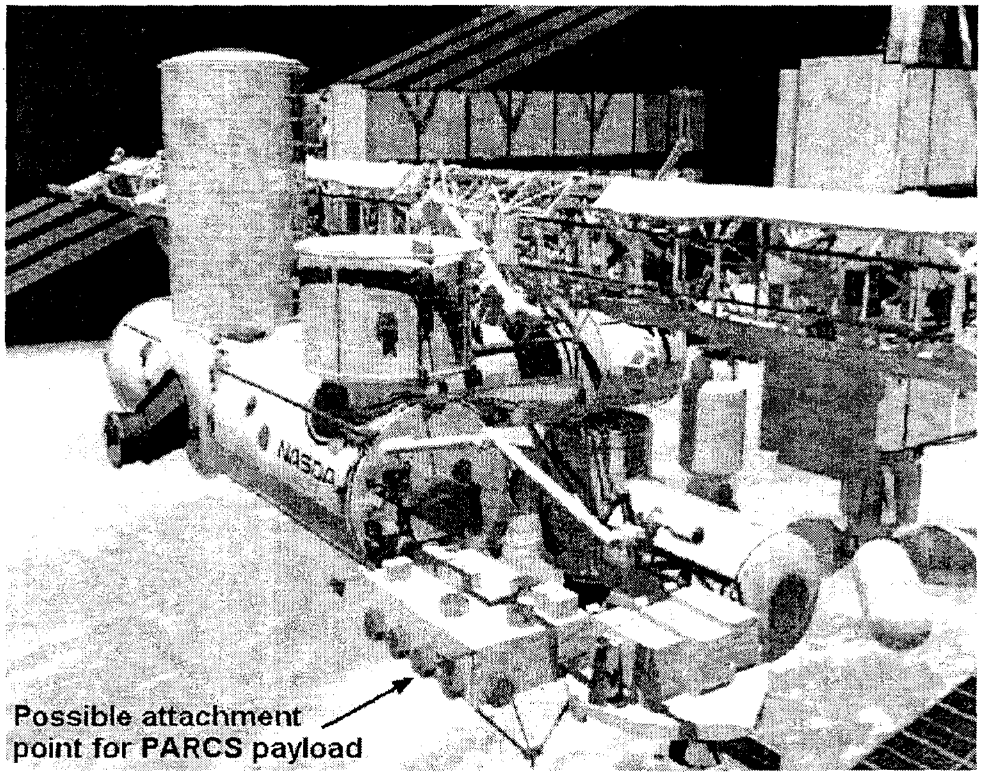


Figure 1. Projected location of PARCS on the ISS.

Figure 2 shows a block diagram of the main space and earth components. The local oscillator is a space-qualified hydrogen maser produced (but never flown) for MIR. The output of the maser 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 at the cesium resonance 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 relatively low-data-rate communication link shown at the top right of Fig. 2.

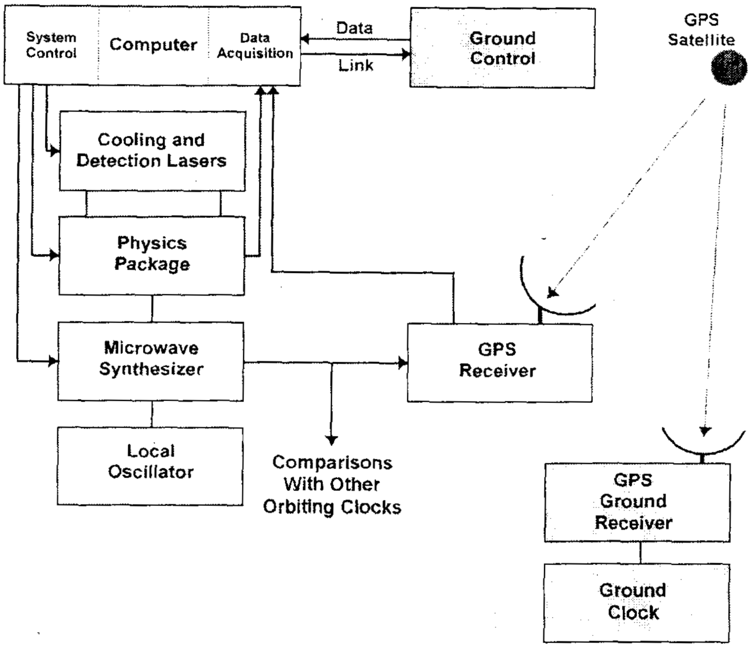
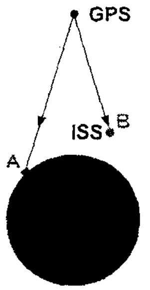


Figure 2. Block diagram of the PARCS experiment showing the major ISS and ground-station components. The ground components are shaded.

Time and frequency are transferred using reception of the GPS carrier (phase) in a common-view method shown schematically in Figure 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 are the difference between readings from the reference clock at that location and from the GPS clock, with an added signal-transit delay. In differencing the data sets acquired at the two points, the GPS clock drops out, and we are left with 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 evaluated quite well. Dramatic improvement over single observations is then obtained by taking and 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.



$$[A - GPS - \vartheta_A]$$
$$- [B - GPS - \vartheta_B]$$
$$A - B - (\vartheta_A - \vartheta_B)$$

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 time transfer, spacecraft tracking, clock stability, and inaccuracy of the ground clock. For the time-transfer-system limits alone, the two curves would continue downward, but measurements are ultimately limited by uncertainties in the position of the ISS.

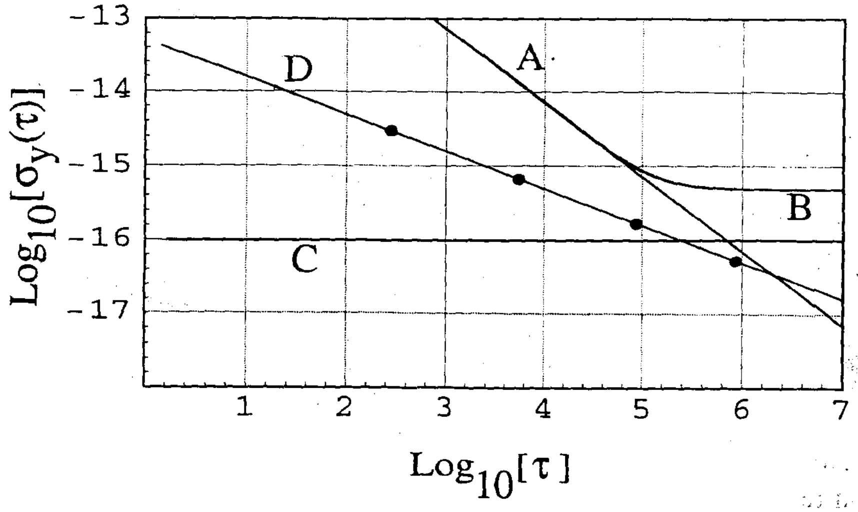


Figure 4. Allan variance plot of the stability limits for the full-level objectives and science requirements. Curve A is the time-transfer limit. Curve C represents the fractional frequency shift from spacecraft tracking (using GPS) at an uncertainty level of 1 m. The clock stability is curve D. Curve B is the composite experimental stability obtained using an integration-by-parts method. This includes contributions from tracking, space-clock stability, and ground clock inaccuracy. The long-term limit is determined by the inaccuracy of the ground clock. The averaging times for 1 pass of the ISS, one orbit of the ISS, 1 day and 10 days are shown from left to right on curve D.

Figure 5 shows a schematic diagram of the proposed clock. The core of the clock, the physics package, is made up of 1) the atom-preparation region where atoms are laser cooled, trapped and launched; 2) a TE_{011} microwave cavity where state preparation is completed by moving atoms from the F=4 ground state to the F=3 ground state; 3) a microwave cavity where atoms are subjected to microwave radiation near the cesium frequency of 9 192 631 770 Hz; and 4) a detection region where laser fluorescence is used to determine whether the microwaves have induced a transition.

The requirements for the laser-cooled clock are selected to achieve a reasonable match with the local oscillator (a hydrogen maser) and the GPS time-transfer receivers. The hydrogen maser achieves a stability (beyond ~50 seconds) of $\sigma_y(\tau) = 5 \times 10^{-14}\tau^{-1/2}$, and this is the stability around which PARCS has been designed. As seen in Figure 4, this stability lies below the limit set by the time-transfer system, thus assuring that the laser-cooled-cesium clock does not degrade the overall stability transferred from the ISS to earth. The system requirements for the clock physics package, the local oscillator, electronic systems, time-transfer systems, and environmental requirements are described below.

The atoms are cooled and trapped using conventional optical-molasses techniques. For traditional frequency modulation, frequency measurements are made on each side of the resonance. A large number of atom balls are launched and detected before the frequency is moved to the other side of the line. This minimizes the stability limit produced by the dead time (the Dick effect). To achieve the desired stability, we estimate that we must launch ~2 balls per second with a transverse temperature of 2 μK and a total of 1×10^6 atoms (in the m=0 state) in each ball at a velocity of 15 cm/s. For a cavity length of 75 cm, this gives a Ramsey time of 5 s. The cycle time (the time spent on each side of the line) is projected to be 15 s. These parameters are within the state of the art, and a trap system was constructed to verify that we could achieve them.

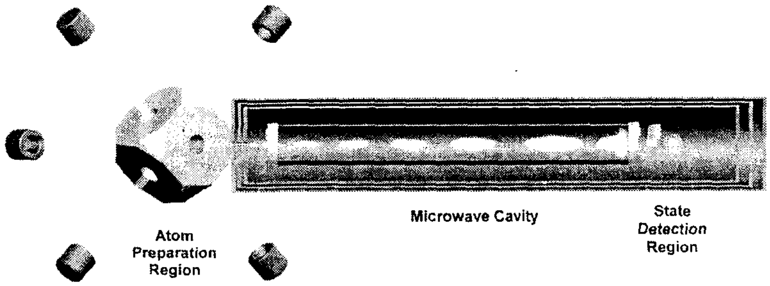


Figure 5. Diagram of the PARCS laser-cooled space clock. Atoms in the source (atom-preparation) region are cooled and trapped and then launched. The state-detection lasers are not shown. State detection involves not only detection of the atoms that have changed states, but also measurement of the number of atoms arriving in each measurement cycle so as to normalize detection to the number of atoms launched and thus remove shot-to-shot noise. Shutters (not shown) at ends of the cavity are closed during laser interactions with atoms to prevent scattering of laser light into the cavity. Three concentric magnetic shields are shown surrounding the microwave cavity and state-detection region.

Two different approaches to locating the center of the resonance line have been studied, and while the conventional approach of frequency modulation remains an option, the very low velocity of the atoms in this clock provides opportunity for a new approach that both reduces the sensitivity of the clock to acceleration noise and increases the duty cycle (that is, reduces the Dick effect). The now favored method 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 discriminator-like response rather than a true resonance. When the phase of the far-end cavity (closest to detection region) is then inverted by 180°, a second, flipped discriminator curve is produced. The intersection of the two curves is a measure of the center of the resonance. The servo-control system used to stay on resonance operates in the same way as the system used for frequency modulation. That is, the amplitudes of signals derived from the two-discriminator curves (180° phase difference) are driven by the servo system to be equal, and this is then the true location of the resonance center. The fact that the system runs on resonance rather than on the sides of the resonance, makes it first-order insensitive to vibrations. This method of interrogation was tested on the NIST cesium-fountain clock, and at an uncertainty level on the order of 1×10^{-15}, the location of the center of the resonance was identical to that found using the conventional method.

This process does not eliminate need for measuring end-to-end cavity phase shift. That is done by varying launch velocity and extrapolating the response to zero velocity. To first order, the frequency shift caused by an end-to-end phase asymmetry is a linear function of the launch velocity. The larger question in this modulation scheme is the short-term control of the relative phases (modulo 90°) at the two cavity ends. The approach is to independently monitor the power reflected from each of the end cavities, and since this provides a measure of the phase in each cavity, to control short-term variations in phase with a fast servo-control system. Phase-noise measurements made using a test TE_{011} cavity and a reflection detector show that it is straightforward to achieve the phase sensitivity needed to achieve this short-term control.

Figure 6 is a simple sketch of the layout of the clock. The cavity outline is the outside of the cavity. The lower portion of the figure shows the system dimensions in greater detail.

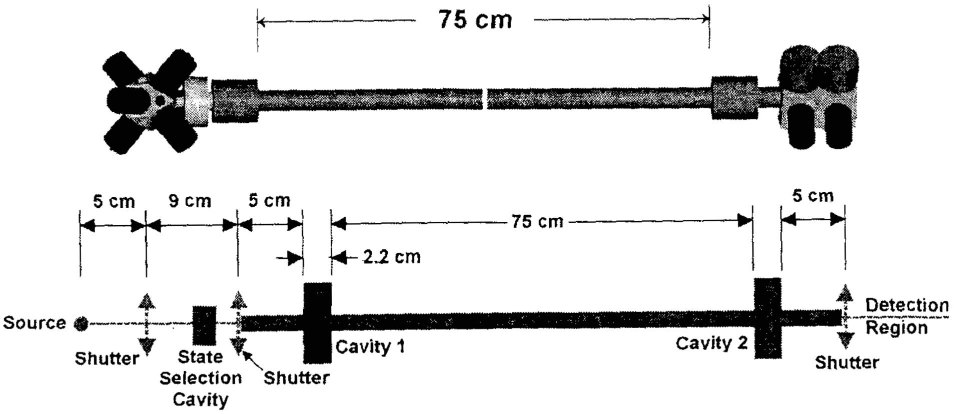


Figure 6. Dimensions for the PARCS laser-cooled clock.

One of the larger systematic frequency shifts to be evaluated and corrected is the spin-exchange frequency shift. This shift is large (0.5 to 1×10^{-15} for typical earth-bound clocks). Fortunately, this shift scales down dramatically with increasing Ramsey time and is projected to be nearly two orders of magnitude smaller for the chosen PARCS parameters. The spin-exchange and other systematic shifts will have to be carefully measured and corrected to achieve the desired long-term stability, but there appear to be no major issues associated with correcting these shifts.

It has long been recognized that the spin-exchange shift in rubidium is much smaller than that in cesium, and therefore it might be a good candidate for advanced atomic clocks. While this is true, the spin-exchange shift is not a limiting consideration for PARCS. There are several advantages to staying with cesium, including the facts that (1) the cavity can be smaller (because the resonance frequency is higher) and that (2) the SI definition of the second is based on cesium. This will allow PARCS to serve as a true primary frequency standard.

3. Prototype Development

A number of components have been either designed or fabricated in prototype form. These include the following.

- The shutters, which are critical to operation of the PARCS clock, have recently been fabricated, and preliminary testing of them has begun. These shutters must produce a minimum of magnetic field and vibration, have an open aperture of 1.0 cm, operate at a rate of at least 10 Hz, and survive $\sim 2 \times 10^8$ actuations.

- Collimators for the trapping and detection lasers, as well as a prototype trapping chamber, have been constructed from titanium, and a prototype for the clock 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 exacting alignment. A jig system for achieving correct alignment before welding has been constructed.

- A design for the microwave cavity is now complete, and fabrication of the cavity will begin soon.

4. Summary

In summary, PARCS development is proceeding on schedule, and all critical issues are being addressed through modeling and prototype construction. It appears that, as long as shutter problems can be solved, the requirements for atom density and systematic frequency shifts should be achievable.

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* Contribution of the U.S. Government, not subject to copyright.

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