PARCS: A LASER-COOLED ATOMIC CLOCK IN SPACE*

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This paper describes progress toward the development of a Primary Atomic Reference Clock in Space (PARCS) and reviews the scientific and technical objectives of the PARCS mission. PARCS is a collaborative effort involving the National Institute of Standards and Technology (NIST), the University of Colorado, the Jet Propulsion Laboratory (JPL), the Harvard Smithsonian Center for Astrophysics (SAO) and the Politecnico di Torino. Space systems for this experiment include a laser-cooled cesium atomic clock and a GPS frequency-comparison and orbit determination system, along with a hydrogen maser that serves as both a local oscillator for the cesium clock and a reference against which certain tests of gravitational theory can be made. In the microgravity environment of the International Space Station (ISS), cesium atoms can be launched more slowly through the clock's microwave cavity, thus significantly reducing a number of troubling effects (including several critical systematic effects), so clock performance can be substantially improved beyond that achieved on earth.

1. Introduction

A more accurate and stable clock in space can achieve several purposes including: tests of gravitational theory, study of GPS satellite clocks, study of neutral atoms in microgravity, and a more accurate realization of the second, which can then be made available worldwide. PARCS[1] and two other atom-clock programs, Atomic Clock Ensemble in Space (ACES)[2] and Rubidium Atomic Clock Experiment (RACE)[3], 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 relativistic frequency shift, which can be determined within an uncertainty about 35 times better than was done previously[4], and local position invariance, which can be tested at an uncertainty about 120 times better than the best current experiments on earth.[4] 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} (1 σ), a factor of 20 better than that presently achieved on earth.

The NASA-funded PARCS mission, which is scheduled to fly in 2005, completed its 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 tested.

2. System Design

The desired location for the experiment (see Fig. 1) is on a forward section of the Exposed Facility (EF) of the Japanese Experimental Module (JEM). This location provides good zenith and nadir views, which are important for time transfer (frequency comparisons). Furthermore, the available power (3 kW), closed-fluid cooling (2 kW), mass allocation (500 Kg) and available space (1.8 × 1.0 × 0.8 m) are well suited to the experimental requirements.

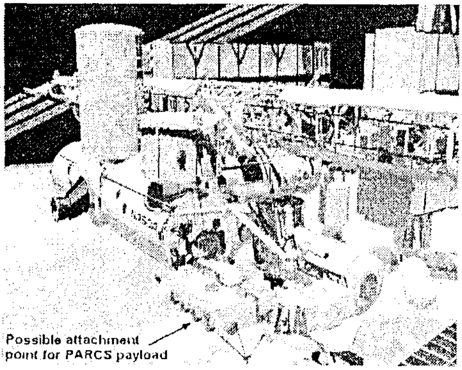

Figure 1. Projected location of PARCS on the ISS.

Figure 2 shows a block diagram of the main space and earth components. The local oscillator is a hydrogen maser that had been developed for the Russian Space Station Mir (but never flown) by the Harvard-Smithsonian Center for Astrophysics.[6] The output of the maser is fed to the low-phase-noise microwave synthesizer,[7] which, under control of the computer, produces synthesized frequency offsets steered to the appropriate resonances in the cesium spectrum. The synthesizer also delivers a cesium-based reference signal 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 near the top right of the figure.

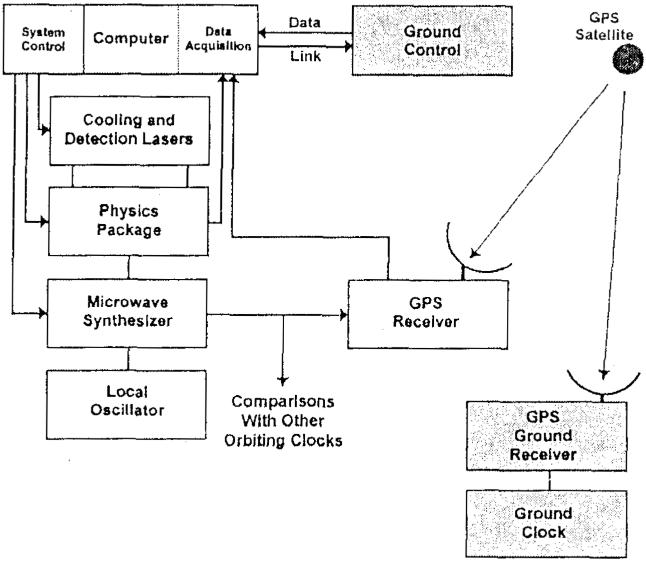

Figure 2. Block diagram of the PARCS experiment showing the major ISS and ground-station components. The ground components are shaded.

Frequency is transferred using reception of the GPS carrier phase in the common-view method. Receivers at the ground station and on the ISS receive common signals from the GPS constellation. The data acquired at each location are the differences 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, leaving the difference between the two clock readings, plus the differential transit delay. This differential delay 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. The objective for this mission is a time-transfer uncertainty of about of 100 ps.

Figure 3 shows the limits imposed by time transfer, spacecraft tracking, clock stability, and inaccuracy of the ground clock. For the time-transfer-system limit alone, the curve would continue downward, but measurements are ultimately limited by other considerations.

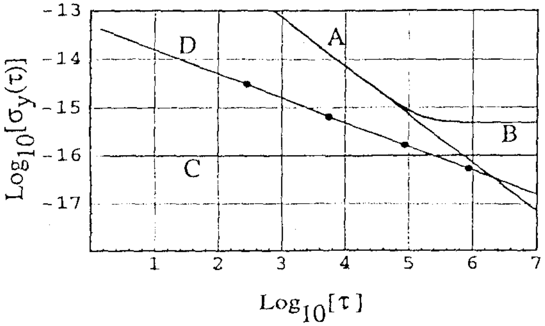

Figure 3. Allan variance of the stability limits for the full-level objectives and science requirements. Curve A is the frequency-comparison limit imposed by a 100 ps time-transfer uncertainty. Curve C represents the fractional frequency shift from spacecraft position tracking (using GPS) at an uncertainty of 1 m. The clock stability is curve D. Curve B is the composite experimental stability obtained from 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 (uncertainty projected to be 5 x 10^{-16} by 2005). 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 by the solid dots on curve D.

Figure 4 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 (not shown in the figure), 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 have been selected to achieve a reasonable match to the local oscillator (the SAO hydrogen maser) and the GPS time-transfer system. The 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 3, 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, and environmental requirements are described below.

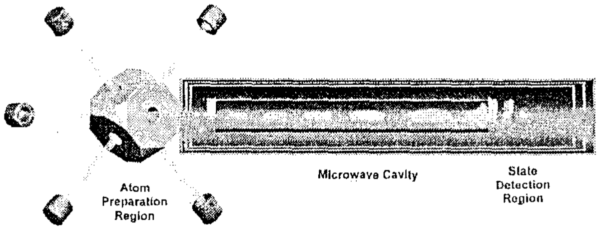

Figure 4. Diagram of the PARCS laser-cooled space clock. Atoms in the source (atom-preparation) region are cooled and trapped and then launched. The state-detection lasers are not shown. State detection involves not only detection of the atoms that have changed states, but also measurement of the number of atoms arriving in each measurement cycle so as to normalize detection to the number of atoms launched and thus remove shot-to-shot fluctuations. 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.

The atoms are cooled and trapped using conventional optical-molasses techniques. Traditional atomic clocks use frequency-modulation methods to find the center of the atomic resonance. A large number of atom balls are launched and detected before the frequency is moved from one side of the line to the other. This minimizes the stability limit imposed by the dead time (the Dick effect). To achieve the desired stability, we estimate that we must launch ~2 balls per second at a velocity of 15 cm/s with a transverse temperature of 2 μK and a total of 1×10^6 atoms (in the m=0 state) in each ball. 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.

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 (a concept first described at a conference in Italy[8] and discussed in more detail in the proceedings of the 2001 IEEE Frequency Control Symposium[9]). 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 the detection region) is then inverted by 180°, a second, flipped discriminator curve is produced. The intersection of the two curves is 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 the 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. One possible 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 phase variations with a fast servo system.

Figure 5 shows a simple outline of the key parts of the physics package along with their dimensions.

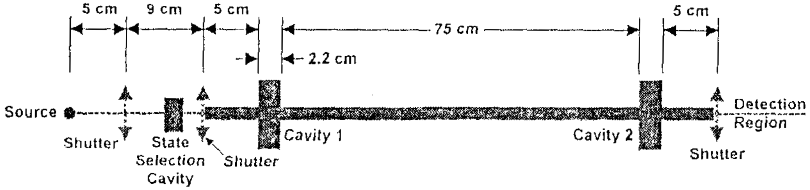

Figure 5. Dimensions for the PARCS laser-cooled clock.

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 for staying with cesium, including the facts that (1) the cavity can be smaller because the resonance frequency is higher, (2) the SI definition of the second is based on cesium, and (3) there are many existing cesium primary standards around the world that can be compared directly with the PARCS clock, yielding improved measurement of the relativistic frequency shift.

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 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 cm, open and close with millisecond time constants, operate at a rate of at least 10 Hz, and should survive ~ 2×10^8 actuations.
- Collimators for the trapping and detection lasers, as well as a prototype trapping chamber, have been constructed of titanium, and a prototype for the clock is under development.
- 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 which uses a number of space-qualified components, is nearing completion.[10]
- 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 technique is being studied as a possible means for assembling a number of the components that require exacting alignment. A jig system for achieving correct alignment before welding has been constructed.
- A design for the microwave cavity was completed, and a prototype cavity has been fabricated. Testing of the cavity has just begun.

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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