A Laser-Cooled Atomic Clock in Space*

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Abstract. This paper describes work aimed at producing a "Primary Atomic Reference Clock in Space (PARCS)," scheduled for flight on the International Space Station in 2004. The microgravity environment of space will allow this clock to achieve an uncertainty ten times lower than can be achieved on earth. The experimental objectives are to measure several relativistic effects on clocks and to provide both time and frequency references available as a international standards accessible to anyone on earth.

INTRODUCTION

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 Politecnico di Torino are collaborating in the development of a laser-cooled-cesium atomic clock for flight on the International Space Station (ISS). The atomic clock, called PARCS (Primary Atomic Reference Clock in Space), will use cesium atoms that are laser-cooled to $\leq 2\ \mu K$ in temperature. The microgravity of space will allow us to increase the transit time of the atoms through the PARCS clock to nearly 10 seconds. At the low velocity commensurate with this transit time, a number of effects (including several critical systematic effects) become much easier to handle, so the performance of the clock can be substantially improved. The Earth's gravitational acceleration limits atom observation time in ground-based clocks to 1 second or less.

This project was funded for flight-definition study in early 1998 under NASA's program on Fundamental Physics in Microgravity. The Science Requirements Document was completed in November 1998 and a Science Concept Review was successfully completed in January of 1999. A prototype clock is now under construction at JPL.

OBJECTIVES

Several relativistic effects on clocks will be studied. We expect to be able to measure the gravitational frequency shift at least an order of magnitude more accurately than was done on Gravity Probe A (Vessot, 1979). Local position invariance will also be studied, and significant advances beyond the best current measurements (Prestage, 1995) are expected. We will also be able to determine the second-order Doppler shift at a level comparable to that of the best current experiments, but even this result should be useful, because our experiment is quite different from the fast-ion-beam experiments performed on earth, and thus tests theory under a different set of conditions.

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Another objective is to improve the accuracy of atomic clocks, that is, our realization of the second. The present second, realized on the ground using cesium-fountain atomic clocks (Clairon, 1996 and Jefferts, 1998), has an uncertainty of slightly more than 1 part in 10^{15}. The Earth's gravitational field limits clock performance by placing a lower bound on the atom velocity. For a clock in space, we project that we can reduce the uncertainty by an order of magnitude or more.

PARCS SPACE SYSTEMS

The experimental arrangement is shown in Figure 1. PARCS requires a high-quality local oscillator, a low-noise microwave frequency synthesizer, state-of-the-art time-and-frequency transfer to the ground, and very good determinations of velocity and position of the ISS using GPS. The performance of these system elements ultimately constrains the performance of the overall system, including the design parameters for the laser-cooled cesium clock. The short-term stability of the laser-cooled clock is limited by the performance of available local oscillators, and the overall uncertainty for the scientific and technological studies is limited by frequency-transfer uncertainties as well as by knowledge of the ISS position and velocity.

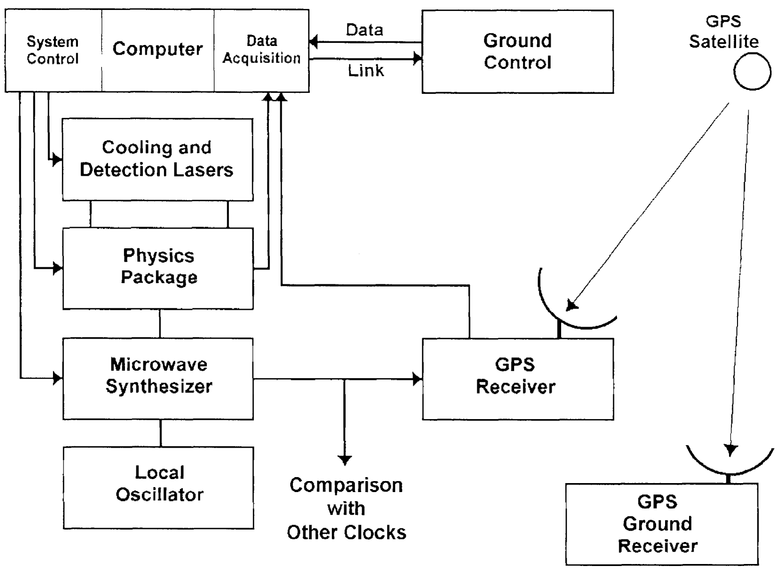

Figure 1. Schematic diagram of the PARCS experiment. The output of the local oscillator, a hydrogen maser, is fed to a synthesizer that supplies the reference signal to the microwave cavity within the clock physics package. An error signal indicating the difference between this local-oscillator reference frequency and the cesium resonance frequency is fed to the control computer to produce a digital error-signal feedback to the synthesizer, thus digitally servo-controlling the synthesizer output to the clock resonance. A lower-frequency synthesized signal proportional to this servo-controlled output serves as a reference for the on-board GPS receiver used in the time-transfer system. This signal is also available for possible comparison with any other high-performance clocks that may fly concurrently with this experiment. The sequencing of laser radiation by the control computer produces the desired laser cooling, laser launching and state detection of atoms within the clock physics package. The difference-signal frequencies that servo-control the local-oscillator output to the cesium resonance constitute measurements of the relative frequencies of the laser-cooled clock and the local oscillator (hydrogen maser). This provides the basis for an equivalence-principle test involving measurement of variations of the difference in rates of the hydrogen maser and the laser-cooled clock. Not shown in the diagram is the GPS receiver system used for determining orbital parameters.

The local oscillator for PARCS is a space-qualified hydrogen maser built by the Harvard Smithsonian Center for Astrophysics (Mattison, 1997). This maser, originally designed to fly on Russia's MIR, has a short-term stability of $\sigma_y(\tau) = 3\times10^{-14}\tau^{-1/2}$ out to 1000 s. PARCS is designed to have sufficient atomic flux to achieve a short-term stability commensurate with that of the maser. Since the system performance is limited by the local oscillator and by frequency transfer to earth, any increase of atomic flux beyond this level contributes nothing toward clock stability. In fact, such an increase would have a negative impact, since it would unnecessarily increase the magnitude of systematic frequency shifts.

The goal for frequency uncertainty (essentially the realization of the second) for the PARCS cesium clock is 3 parts in 10^{17}. This is limited by projected uncertainties in systematic frequency shifts and the duration of the experimental measurement periods. The time-transfer system, based on carrier-phase GPS measurements, limits the overall experimental accuracy. Preliminary simulations conducted at JPL show that the JPL-designed GPS receiver system should be capable of determining the position and velocity of the ISS (within < 5 cm and < 1 mm/s), as well as transferring the clock time at a level of ≤ 100 ps to any point on the earth. Preliminary tests of the GPS receiver will be obtained during an upcoming shuttle flight of the receiver. It is interesting to note that the ISS positions and velocities are not supplied by the station itself with sufficient accuracy to do these experiments.

The laser-cooled atomic clock will operate in a pulsed mode, injecting a group of atoms every few seconds into the clock (shown in Figure 2). The physics package of the clock consists of: (1) a source region where cesium atoms are trapped by intersecting laser beams, cooled to about 2 μK and launched at low velocity into the clock; (2) a microwave-cavity region where the cesium clock transition at 9.192 631 770 GHz is probed; and (3) a detection region where the states of atoms emerging from the microwave cavity are determined. The requirements for the source have already been met by systems demonstrated at a number of laboratories including NIST, and laser systems now under development are well within the state of the art. The microwave cavity (Jefferts, 1998) and the transit of the atoms through the cavity have been well modeled, and no difficulties are expected with this portion of the system. Because of the advantages arising from the microgravity environment, performance for the digital servo-control system of the clock is actually less demanding than for systems now running at NIST. Finally, a microwave synthesizer, has been constructed and tested and well surpasses mission requirements (Sen Gupta, 1999).

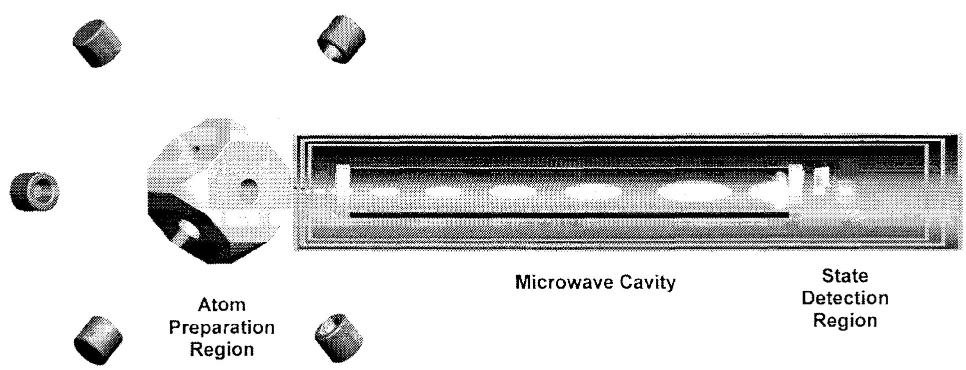

Figure 2. Diagram of the PARCS laser-cooled space clock. Atoms in the source area are cooled and trapped and then launched through the microwave cavity. The lasers used for detecting the states of the atoms exiting the cavity are not shown. State detection involves measuring the number of atoms arriving in each measurement cycle so as to normalize detection to the number of atoms launched and thus remove shot-to-shot noise. Shutters (also not shown) at both 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.

While there are still some questions related to the integration of the experiment into the ISS, there appear to be no fundamental obstacles to performing this experiment in space. The full performance of the system cannot be achieved without the microgravity environment, so it will be important to devise a series of ground-based tests that can prove that the expected performance is achievable.

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