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-beam atomic clock for flight on the International Space Station (ISS). The clock, named PARCS (Primary Atomic Reference Clock in Space) is designed to perform certain tests of relativity and fundamental physics and to serve as a primary frequency standard.

LOCAL OSCILLATOR AND TIME-TRANSFER

The experiment requires both a high quality local oscillator (LO) as well as state-of-the-art frequency transfer from PARCS to the ground. The performance of these systems ultimately constrains the design parameters for the cesium clock portion of the experiment. The short-term stability is fundamentally limited by the available LOs, and the overall experimental uncertainty is limited by the frequency transfer uncertainties as well as knowledge of the ISS position and velocity.

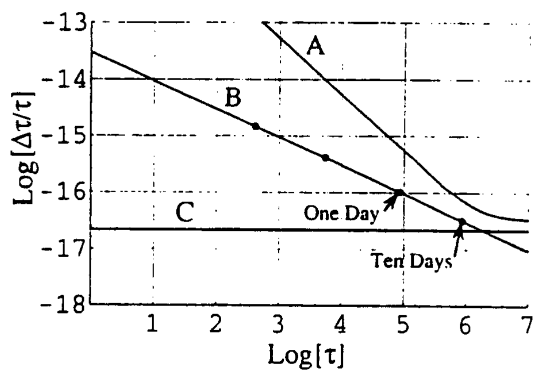

Figure 1 - *PARCS stability and uncertainty considerations. Curve A shows the time-transfer stability at 50 ps uncertainty and does not include the effect of a ground clock uncertainty. Curve B shows the cesium clock stability, $\sigma_y(\tau) = 3\times10^{-14}\ \tau^{1/2}$. Curve C indicates the contribution due to station position uncertainties (20cm) for this case.*

The local oscillator planned for PARCS is a space-qualified hydrogen maser built by SAO [1]. This maser is designed to have a short term stability of $\sigma_y(\tau)= 3\times10^{-14}\tau^{-1/2}$ and to hold this stability out to a time of at least 1000 s. PARCS is designed to have sufficient atomic flux to achieve a short term stability commensurate with that of the maser. While it is possible to have atomic stabilities significantly better than $3\times10^{-14}\ \tau^{-1/2}$, the chosen stability is limited by the performance of the local oscillator. Higher atomic fluxes, while increasing the atomic stability, contribute nothing toward clock stability and simultaneously increase systematic frequency shifts.

The goal for the frequency uncertainty in the PARCS cesium clock is 3×10^{-17}. This is limited by systematic frequency shifts and the projected experimental measurement periods. Once again, while lower clock uncertainty could be achieved, it would contribute nothing to the overall experimental program and would, as a result of limitations imposed by the time and frequency transfer process, be unavailable "on the ground." The time transfer system, based on carrier-phase GPS measurements, limits the overall experimental accuracy as can be seen in Fig. 1, which shows components of the experiment stability as a function of averaging time. Preliminary simulations conducted at JPL show that the time transfer system

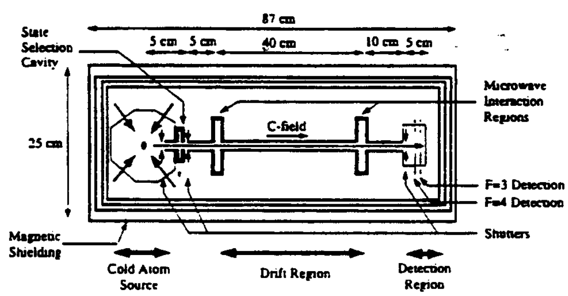

Figure 2 - *Schematic diagram of the PARCS cesium clock physics package. The C-field region encompasses the source and detection regions. The scales shown are approximate.*

should be capable of determining the position and velocity of the ISS, as well as transferring the clock frequency at levels which are necessary for this experiment. It is interesting to note that the ISS velocities and positions are not supplied by the station itself with sufficient accuracy to do these experiments.

CESIUM CLOCK DESIGN OVERVIEW

The cesium source, shown to the left in Fig. 2 is a pure lin⊥lin optical molasses source. The 1,1,1 launch geometry was chosen to avoid an optical beam down the flight axis of the clock. In order to achieve the desired stability the source will launch approximately 5×10^6 m=0 atoms per ball with an atom temperature of 2 μK at a rate of 2 Hz (3 to 10s Ramsey time, 10 launches per lineside). PARCS will operate with a square-wave frequency modulation scheme with several (of order 10) balls of atoms being measured on one side of the Ramsey fringe before jumping to the other side of the fringe. This arrangement matches the cesium performance to that of the Hydrogen maser allowing a long attack time on the frequency servo with no loss of signal-to-noise ratio. For other local oscillator types different parameters would be more appropriate.

The laser for both the source and detection region (see below) will be either an extended cavity diode laser or a distributed Bragg reflector (DBR) type laser at 852 nm locked to a saturated cesium absorption line on the F=4 manifold. This laser drives a tapered amplifier (TA) with an output of 500 mW. A DBR laser, locked to the F=3 manifold by saturated absorption, provides the re-pump power for both the molasses and detection regions. A schematic of the preliminary optical-system design is shown in Fig. 3.

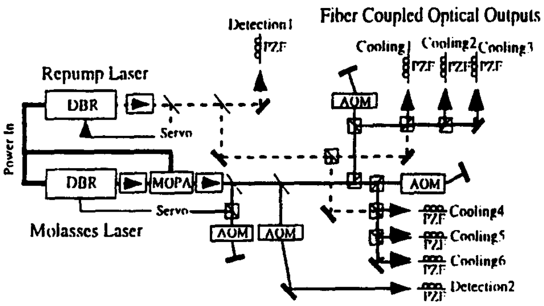

Figure 3 - *Schematic diagram of a preliminary optical design for PARCS. The optical molasses is generated with a TA (injected either with a DBR or an external cavity laser), while repumping is done with a DBR. The following symbols are used in the diagram; TA: tapered amplifier, DBR: distributed Bragg reflector laser, AOM: acousto-optic modulator, PZF: polarizing optical fiber.*

The atoms are accelerated out of the molasses region (to the right in Fig 2) through a shuttering system and into a state selection cavity. The atom-shuttering system (in vacuum) allows the molasses and atom detection regions to operate while atoms are in the Ramsey cavity. Without shutters, this would be impossible as resonantly scattered light would produce a large uncorrectable frequency shift.

In normal operation, the state-selection cavity provides a π-pulse which transfers $|F=4,m=0\rangle$ atoms to the $|3,0\rangle$ state. The remaining F=4 atoms are then removed with an optical pulse. State selection greatly reduces the spin-exchange frequency shift by removing atoms which contribute to the frequency shift but not to the signal.

The sample of $|3,0\rangle$ atoms then enters the Ramsey cavity, which in this clock consists of two TE_{011} cavities resonant at 9.192 GHz coupled with a resonant structure. The cavities, similar to those used in the new NIST cesium fountain clock NIST-F1, exhibit exceedingly small phase variations across the relatively large apertures through which the atoms travel [2].

After microwave interrogation the atoms exit the Ramsey cavity through a shutter. The number of atoms in the F=4 state are then measured by fluorescence, followed by an optical "clean out" pulse which removes the F=4 atoms. The remaining atoms (F=3) are then pumped into F=4 and their number measured, again by fluorescence. This detection procedure gives the fractional number of atoms having made the clock transition. The process is described more fully in references [3, 4].

When this launch, interrogation, and detection cycle has been completed for a predetermined number of atom balls the frequency of the microwave synthesizer is tuned to the other side of the Ramsey fringe and the measurement is repeated.

SYSTEMATIC FREQUENCY BIASES

Many of the traditional thermal-beam clock biases are greatly reduced in this clock as a consequence of the long Ramsey times achievable in the micro-gravity environment. However the end-to-end cavity phase shift, absent in terrestrial cold-atom fountains, is reintroduced as a result of the more traditional Ramsey interaction geometry. Fortunately, the low launch velocity dramatically reduces the magnitude of this effect.

The significant frequency biases are the spin-exchange frequency shift, the second-order Zeeman shift, the black-body shift, and the end-to-end cavity phase shift. These are discussed below.

The spin-exchange shift contributes a frequency uncertainty of about 1×10^{-15}, currently a major source of frequency uncertainty in terrestrial cesium-fountain clocks. The spin-exchange shift in a clock of this type can be written as

$$\frac{\Delta f}{f} = A[(\frac{hl}{L})(\frac{\rho_1 + \rho_3}{2} - \overline{\rho_2}) + \overline{\rho_2}]$$

where h is a parameter of order 1 which depends on the excitation, l is the microwave cavity length, L is the length of the Ramsey zone, ρ_1 is the atomic density in the first microwave cavity, $\overline{\rho}_2$ is the average density in the Ramsey zone, and ρ_3 is the atomic density in the second microwave cavity [5]. The spin-exchange coefficient A (for the m=0 state collision) measured by Clairon et al. is about $2\times10^{-21}/\text{cm}^3$ [3]. As shown in Fig. 4, the long Ramsey times associated with the micro-gravity environment allow smaller average densities, thereby reducing the spin-exchange frequency shift to below 1×10^{-16}. The micro-gravity environment also allows easier extrapolation to zero density as a result of the large range of Ramsey times that can be used to evaluate it. This shift can therefore be corrected to an uncertainty less than the design goal of 3×10^{-17}.

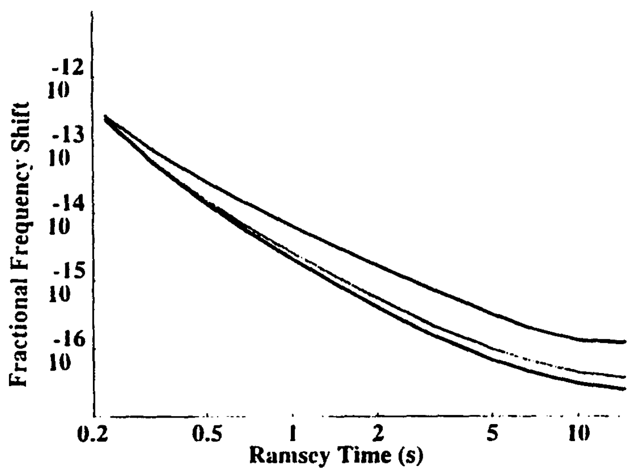

Figure 4 - *Modeled spin exchange shift as a function of toss velocity for constant stability of $\sigma_y(\tau) = 3\times10^{-14}\ \tau^{-1/2}$. For all cases the transverse atom temperature is 2 μK, and the Ramsey cavity is 40 cm long. This model is for a point source, The upper curve (at the right edge of the figure) is for one atom ball per line side. The next curve below that is 5 balls per line side, while the lowest curve is for 10 balls per lineside. Using 10 balls per lineside and 10 second Ramsey times gives a spin exchange shift of less than 5×10^{-17}.*

In PARCS, the Rabi width will be about 2 Hz (depending on launch velocity) and a 10 nT C-field will separate the Zeeman lines from the clock (m=0, Δm=0) transition by 70 Hz, more than sufficient to avoid Ramsey pulling. This low C-field value leaves the total frequency shift associated with the second-order Zeeman at 5×10^{-16}. This shift can be corrected to well below 10^{-17}. The effect of magnetic-field inhomogeneity is also reduced. The magnetic field can be modeled as $H(z) = H_o[1-\epsilon f(z)]$, where z is the coordinate along the atomic beam axis, ϵ is a scale factor and $|f(z)| \leq 1$. If the m=1 line is used to measure the mean magnetic field, then the error in the quadratic Zeeman shift as a result of field inhomogeneity can be shown to be

$$\frac{\Delta f}{f} = \frac{427x10^8 H_o^2}{\omega_o} \epsilon^2[\langle f(z)\rangle^2 - \langle f(z)^2\rangle] \quad .$$

With an extreme case of 10 % inhomogeneity and the worst case where $\langle f(z)\rangle^2 - \langle f(z)^2\rangle = ½$, the frequency shift is of order 2×10^{-18}. The magnetic shields must be capable of reducing external field fluctuations to the level of 100 pT to keep frequency shifts below 10^{-17}. Shielding at this level, in the presence of 10^{-4} T (1 G) magnetic-field variations, has been demonstrated by, for example, the SAO maser to be used in this experiment.

PARCS is designed to operate slightly above room temperature (37 °C). At this temperature the blackbody-radiation-induced frequency shift is about 2×10^{-14} and is not presently correctable to 10^{-17} due to a lack of knowledge of the precise coefficients in the frequency-shift formula.

In thermal-beam primary frequency standards, end-to-end cavity phase shifts are a significant source of error. A common method of correcting for this shift is to send atoms both directions through the clock. The end-to-end cavity phase shift can be canceled by properly combining the results of the measurements in the two directions. While this approach is feasible in a space clock, we have elected instead to take advantage of the fact that, in a cold atom beam clock in a micro-gravity environment, the Ramsey time can readily be varied over a wide range of values. Figure 5 shows the frequency shift for a mono-velocity group of atoms and a realistic end-to-end cavity phase shift in a beam clock as a function of the atom-launch velocity. The extrapolation to zero launch velocity gives the frequency corrected for end-to-end cavity phase shift. The effect of the velocity distribution of the atoms must be modeled.

However, even after accounting for the velocity distribution of the atoms we project that, evaluation of the end-to-end phase shift can be made to well below 10^{-17}.

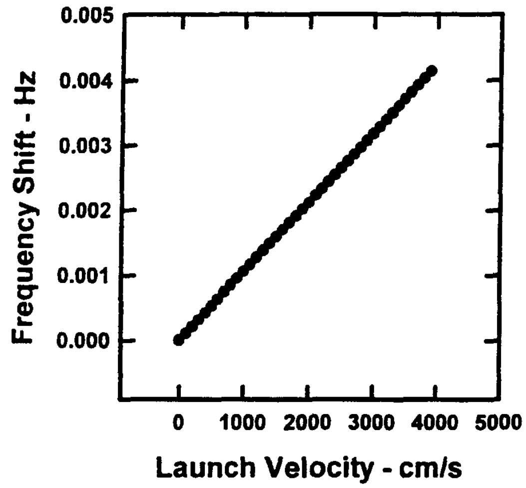

Figure 5 - *Clock frequency as a function of launch velocity. The slope of the line is the end-to-end cavity phase shift divided by* 2π *times the Ramsey length. The zero-velocity intercept of the line is the clock frequency for zero end-to-end cavity phase shift.*

A prototype of the microwave synthesizer, based on electronics that can be space-qualified, has been constructed and tested [6]. The performance of this synthesizer will easily support the projected stability and uncertainty of the PARCS cesium clock. Spectral frequency biases are therefore not expected to be an issue.

Our thermal-beam standard, NIST-7, routinely splits a Ramsey fringe by more than one part in 10^6 whereas PARCS will only need to split its (50 mHz wide) fringe by a part in 10^5. Digital servo-system errors are thus not expected to be significant.

The following list of biases are reduced to insignificant levels in this clock and are not discussed here: Rabi pulling, Ramsey-pulling, Majorana transitions, distributed cavity phase shift, Bloch-Siegert shift, second-order Doppler shift, and cavity pulling.

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