Performance of the PARCS Testbed Cesium Fountain Frequency Standard

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***Abstract*—A cesium fountain frequency standard has been developed as a ground testbed for the PARCS (Primary Atomic Reference Clock in Space) experiment -- an experiment intended to fly on the International Space Station. We report on the performance of the fountain and describe some of the implementations motivated in large part by flight considerations, but of relevance for ground fountains. In particular, we report on a new technique for delivering cooling and trapping laser beams to the atom collection region, in which a given beam is recirculated three times effectively providing much more optical power than traditional configurations. Allan deviations down to 10^{-15} have been achieved with this method.**

Keywords- cesium, fountain, light shift, frequency standard, atomic clock

I. INTRODUCTION

In the PARCS (Primary Atomic Reference Clock in Space) experiment, the frequency of a laser-cooled cesium atomic clock operating in a microgravity environment aboard the International Space Station (ISS) is to be compared to a cavity oscillator on the ISS as well as to an accurate clock on the ground (via GPS). NASA's Jet Propulsion Laboratory (JPL) has worked with the PARCS principal investigator team at the National Institute of Standards and Technology (NIST) to design the flight payload for PARCS as the first flight of the Laser Cooling and Atomic Physics (LCAP) program. The scientific goals and conceptual mission description include realization of the second, study of the relativistic frequency shift, the gravitational frequency shift, local position invariance, and the global positioning system, and Kennedy-Thorndike and Michelson-Morley experiments.

A cesium fountain has been built at JPL to mirror (to the extent possible) design concepts for PARCS and to serve as a testbed for candidate implementations and configurations for the flight payload. In this paper, we report on the performance of the fountain and describe some of its characteristic design features. In addition, we report a new technique for delivering the cooling and trapping laser beams to the atom collection region: we recirculate laser light through the collection region, replacing six orthogonal beams (in two pairs of three) with two beams each making three passes through the chamber. To our knowledge, this recirculation technique has not been reported in other fountain systems. Advantages include simplification of the laser system, higher optical power throughput, fewer optical and electrical connections, and simplification of intra-beam power balancing.

The research described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

II. FOUNTAIN DESIGN FEATURES

The fountain was designed to meet the challenges expected for the Cesium Physics Package (CPP) for flight as a way of validating and informing the evolving flight designs, some of which are described in [1]. Fig. 1a shows the lower portion of the physics package while Fig 1b shows the whole fountain (without electronics), respecting the volume constraints for flight as they were understood at the time. Key features of the design include: magnetic shielding of the entire physics package (no magnetic trim coils in the atom collection chamber), all laser beams delivered to the physics package via optical fiber, no mechanical adjustments of optics on the fountain (everything bolts on as built), welded re-entrant windows in titanium and copper walls, and a re-entrant "spill proof" cesium source. We describe the magnetic shielding and cesium source design below, and elaborate on the laser beam delivery method in the next section.

The magnetic shielding (Fig. 1c) includes four layers of shields, plus a field cancellation coil on the third shield out for future implementation of active shielding. Three of these four layers surround the entire vacuum envelope while one layer shields only the Ramsey region. The magnetic field in the atom collection region is designed to be less than 1 mG. The passive shielding effectiveness of the four shields together was measured to be 140,000. For some of the measurements presented in this paper, we removed the inner of the three shielding layers surrounding the entire vacuum envelope in order to fit the new collection region recirculation optics.

The cesium reservoir for PARCS needed to operate in the absence of gravity and not contaminate the atom collection region for any continuous rotation of the apparatus during testing. It also had to be free of particulates (such as glass) which could float into the critical regions of the apparatus on orbit, and operate in a narrow range of temperatures, either above or below the melting point of cesium. The design and prototype are shown in Fig. 2. The "spill proof" design is essentially a tube within a tube that prevents liquid cesium from contaminating the atom collection region. Cesium was distilled into the reservoir, which was then pinched off, sticking out only 0.0125 m from the mini-conflat gasket. The reservoir as built in the prototype has a spill-proof capacity of 0.7 cm^3, enough for over 1.3 gm of cesium. Something less than 1 gram

of cesium was loaded into the reservoir approximately two years ago.

III. "12-CUBE" RECIRCULATION OF BEAMS

Laser cooled atomic fountains generally use six orthogonal laser beams to trap and cool atoms into a 3-D optical molasses in the atom collection region. With the 1-1-1 geometry we use, these trapping/cooling beams are subdivided into three "up" beams whose resultant propagation vectors point up, and three "down" beams whose resultant propagation vectors point down. In addition, opposing beams have opposite linear polarizations (lin-perp-lin configuration). We first discuss our initial design and implementation delivering six independent optical fibers to the atom collection region, and then present the new recirculation technique which delivers just two optical fibers.

Our original (and the traditional) design and implementation delivers each of the six beams independently to the vacuum system via polarizing maintaining fibers. Six collimators are bolted onto the atom collection chamber with no mechanical adjustments (Fig. 3a), whereas typical fountain designs provide alignment capability for these cooling beams. Successful cooling and fountain operation was confirmed, despite the lack of mechanical adjustability, by measurement of signal-to-noise ratios (SNR) up to 500 and Allan deviations down to 1.0×10^{-13} at 1 second using a technique that was *insensitive* to LO (local oscillator) noise. This technique is described in the next section.

With our new recirculation technique, however, just two optical fibers are delivered to the physics package: one to generate the "up" beams, and one with oppositely polarized light to generate the "down" beams. Each of these two fibers creates a beam which recirculates a total of three times through the atom collection region using transmission and reflection off of polarizing beamsplitter cubes, to recreate the familiar six lin-perp-lin beams. The order of the beams is such that within each pair of counter-propagating beams the power is balanced, while the power is reduced on each subsequent pass due to a small amount of absorption and reflection losses from the beamsplitter cubes. The recirculation optics are bolted onto the atom collection chamber, again, with no mechanical adjustability as shown in Figs. 3b-d. These optics consist of 12 polarizing beam splitter cubes and three half-wave plates as shown from two orthogonal views in Fig. 4. In Fig. 4 as well as in Fig. 3b, orange traces the path of the "up" beam, and purple traces the path of the "down" beam. As mentioned previously, one of the four magnetic shields is removed to accommodate the recirculation optics.

Since a single laser is typically used to generate the three "up" (or "down") beams in the traditional design, our new technique of recirculating one beam three times provides nearly three times more optical power than splitting the single beam into three and sending each independently to the collection area. This configuration allows trapping of the same number of atoms at lower total optical power, or alternately more atoms at the same power. In addition, this technique reduces the number of fiber couplings, fibers, and collimators from six to three (one "up" fiber, one "down" fiber, and a 3rd fiber for the "repumper" laser not discussed). It also uses fewer monitor photodiodes, and el iminates the difficulty of maintaining constant power ratios from one beam to the next within a triplet

Before implementing this new recirculation technique, we tested the effect of potential beam imbalances introduced by common mode or differential optical power loss from one pass through the atom collection region to the next. Common mode power loss arises if both the "up" and "down" beams are attenuated by the same factor on each pass, for example by transmission loss through equal numbers of cubes or by absorption due to the cloud of cesium atoms. This absorption was measured to be < 2.5% for the largest atom cloud we could load using the original 6-beam delivery technique, although if one uses more optical power with the recirculation technique, the absorption could be higher. The use of an optical molasses with large optical beams keeps the absorption minimal for a given number of atoms in the cloud. Differential power loss arises if the "up" and "down" beams suffer different attenuations on each pass, for example if the polarizing beam splitters have different reflectivities, the half-wave plates have different transmission losses, or the half-wave plates are not rotated to the ideal angles.

Fig. 5a shows a measurement which simulates the expected repercussions of common mode loss in the "12-cube" technique, where the number of atoms successfully launched and returned to the detection area is plotted as a function of the percentage of light lost for each of the three passes through the atom collection region. These data were taken by launching atoms using the original 6-beam delivery method but adjusting the power of each pair of beams as needed, keeping each "up" beam still balanced with its corresponding "down" beam and keeping the total power constant. Fig. 5b shows the effect of differential power imbalances between one "up" beam and it's corresponding "down" beam, and Fig. 5c shows the same differential effect for all the "up" beams vs. all the "down" beams -- again keeping the total power constant.

These measurements show that the atom return number does not vary by more then 10-20% for typical expected power imbalances < 10%. Indeed, in the next section we show that good fountain stability and performance has been achieved using this new recirculation technique. Higher atom numbers were confirmed, however, higher atom temperatures also resulted: ~10 μK as opposed to the ~1 μK measured using the traditional 6-beam technique. Still, atom return numbers were approximately the same for the two techniques, because more atoms can be collected and launched with the new method. The high temperatures were not viewed as intrinsic to the recirculation technique based on the measurements shown in Fig. 5. It is plausible that the high temperatures were caused by misalignments of the resultant six beams, because we affixed the polarizing beam splitters to their mounting plates without trying to compensate for their steering imperfections and with a mounting system that clipped part of the beams.

IV. FOUNTAIN PERFORMANCE

Fountain performance shown in Fig. 6a validates that the 12-cube recirculation technique can produce stability comparable to the traditional 6-beam technique [2]. Atoms are launched at 4.1 m/s, state selected in the F=3, m=0 hyperfine

level, and then exposed to a $\pi/2$ microwave pulse on their way up through the Ramsey cavity and on their way down. The free-flight time is ~0.5 s; microwaves in the Ramsey cavity are on resonance with the F=3, m=0 → F=4, m=0 transition at 9,192,631,770 Hz. Phase modulation is implemented by shifting the microwave phase at apogee either 90 deg or 270 deg on alternate launches. Return atoms are detected in both the F=3 and F=4 hyperfine states and normalized by the total detected. Frequency sensitivity is determined by fitting the slope of the central Ramsey fringe (Fig. 7). Allan deviations shown in Fig. 6a fit the line $2.4 \times 10^{-13}/\tau^{0.55}$ and reach 0.5 - 1.3 x 10^{-15} at 6.6 hours. Corresponding Allan deviations for the F=3, m=1 → F=4, m=1 magnetic field sensitive line are shown in Fig. 6b.

Microwaves are derived from mixing a 9.2 GHz DRO (dielectric resonant oscillator) signal with ~7.4 MHz from a synthesizer. The synthesizer and the DRO are locked to a LO maser signal distributed from a nearby building via a fiber-optic distribution assembly. The maser has a clean-up loop with a very stable crystal oscillator and typically has short-term stabilities near 1 x 10^{-13} at a second. Fig. 8 shows Allan deviations comparing this reference maser to another maser over the same time period in which the Fig. 6a data were taken.

In order to determine if our signal-to-noise ratio was shot-noise limited and also to deduce how much of the short-term instability was due to the LO, we took data that was *insensitive* to frequency fluctuations. This was done by eliminating the phase modulation and reducing the microwave power so that the atoms only experienced $\pi/4$ pulses rather than $\pi/2$ pulses; the microwaves were still resonant with the m=0 → m=0 transition. In this way, half the atoms still came back in the F=3 state, and half in the F= 4 state. This technique is in common use. Typical one second Allan deviations were 1.4 x 10^{-13}, so assuming the LO noise adds in quadrature, it contributed ~2 x 10^{-13} to the one second Allan deviation in Fig. 6a's data. This is consistent with expectations from the maser instability when taking into account LO aliasing [3,4]. Fig. 9 shows one second Allan deviations and corresponding SNRs measured in the same way -- with $\pi/4$ pulses -- but varying the number of launched atoms. It shows the expected dependence of the SNR varying linearly with the square root of atom return number, and that the fountain data are shot-noise limited up to SNRs ~ 500.

V. MITIGATION OF LIGHT SHIFT WITHOUT MECHANICAL SHUTTERS

Several years ago we proposed operating the fountain without mechanical laser shutters while keeping the light shift below 10^{-17} [5]. In this proposed technique, light intensity is reduced during the free-flight time using a single pass (SP) AOM (acousto-optic modulator), and the light shift is further reduced by causing slave lasers to run off resonance using a double pass (DP) AOM as shown in the Fig. 10. We have now verified this works down to the 2 x 10^{-15} level, limited only by statistics. Table I shows the relative light shifts for various combinations of attenuation as compared to the configuration in which light is attenuated with both a single and a double pass AOM. The table shows that using just the SP or just the DP gives > 10^4 reduction in absolute light shift, thus using both SP and DP, we would expect > 10^8 reduction in light shift. Better limits will be attainable after collecting more data.

CONCLUSION

This fountain, built to aid in the design and implementation of the PARCS flight design, has demonstrated good stability using a new recirculation technique for beam delivery. In addition, the traditional 6-beam technique, as implemented with no mechanical adjustemtns on the physics package, has produced low temperatures and shot-noise limited performance up to SNRs ~ 500.

Lastly, we validated a new technique for reducing light shift at the 10^4 level using a DP AOM injection locking a slave laser. Longer sets of data should be taken to confirm that this method can eliminate the need for shutters.

ACKNOWLEDGMENT

As a testbed for the PARCS experiment this work benefited from contributions by many of the PARCS team members. Command and control with traceability to the flight system were implemented by a team at JPL including Steve Cole, Brian Franklin, Tom Garvey, Richard Guerrero, Vahag Karayan, Erik Peterson, Phil Yates, and George Wells. Electronics support included contributions by Ted Ozawa, Tom Radey, and Rudy Vargas, from JPL. John White provided considerable laboratory support. The microwave cavities were built by Steve Jefferts at NIST. Eric Burt performed the measurement of the passive shielding effectiveness.

TABLE I. MEASURED LIGHT SHIFTS

Attenuation Configuration	Fractional Frequency Shift (relative to SP+DP)
NO attenuation (i.e. full light shift)	2 x 10^{-11}
Just Single Pass AOM	< 2 x 10^{-15}
Just Double Pass AOM	< 2 x 10^{-15}
Mechanical Shutters and Single and Double Pass AOM	< 4 x 10^{-15}

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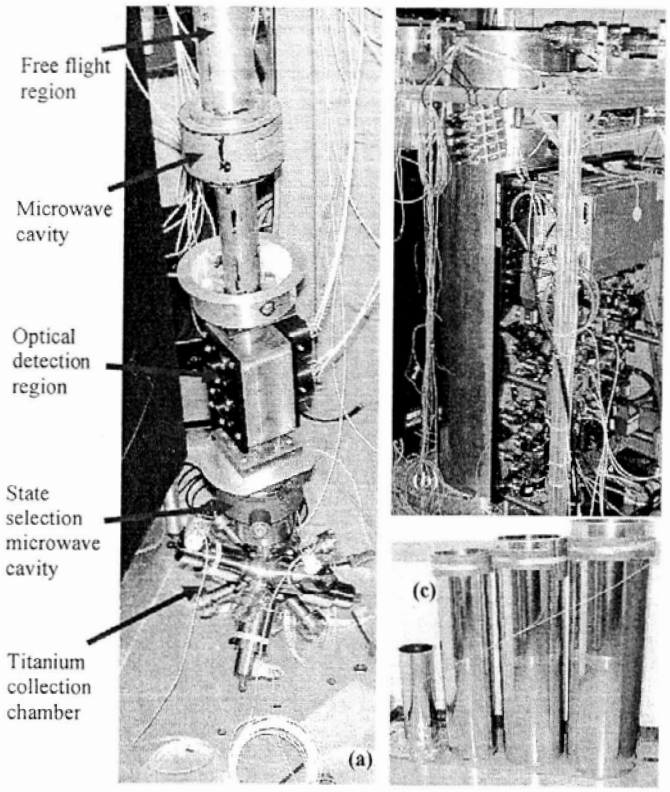

Figure 1. Lower section of fountain vacuum system (a), full fountain without electronics (b), and fountain shields (c).

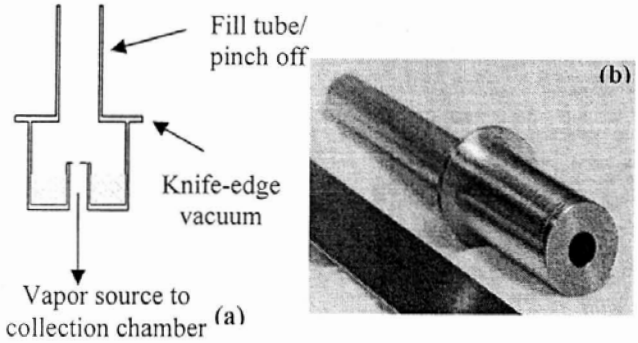

Figure 2. Design (a) and prototype (b) cesium reservoirs.

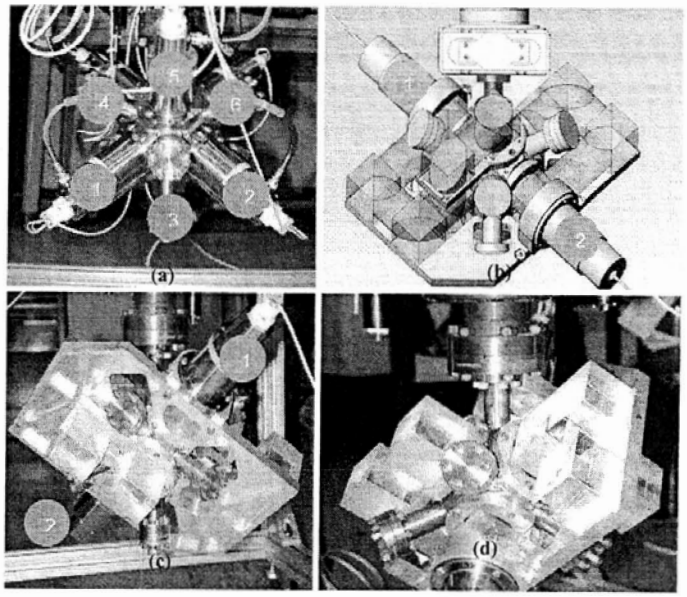

Figure 3. Beam delivery optics for traditional 6-beam configuration (a). Beam delivery optics for new 12-cube recirculation technique (b-d). Rendering in (b) shows optical beam-paths. Photographs in (c) and (d) show bottom and top view, respectively.

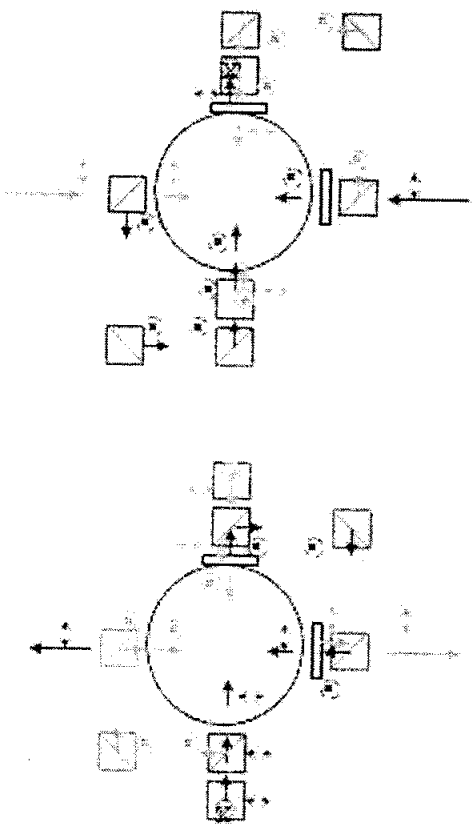

Figure 4. Two orthogonal views tracing beam paths of the "up" and "down" beams in the 12-cube optics apparatus. Single ended arrows show beam direction, and double ended arrows show polarization. Lower drawing view is rotated by 90 degrees about the vertical axis.

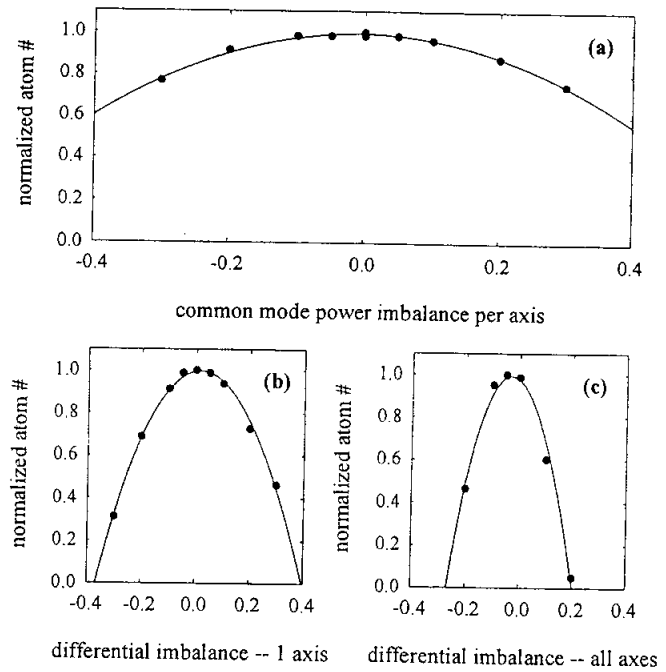

Figure 5. Atom return numbers for various types of pwer imbalances in the cooling/trapping beams.

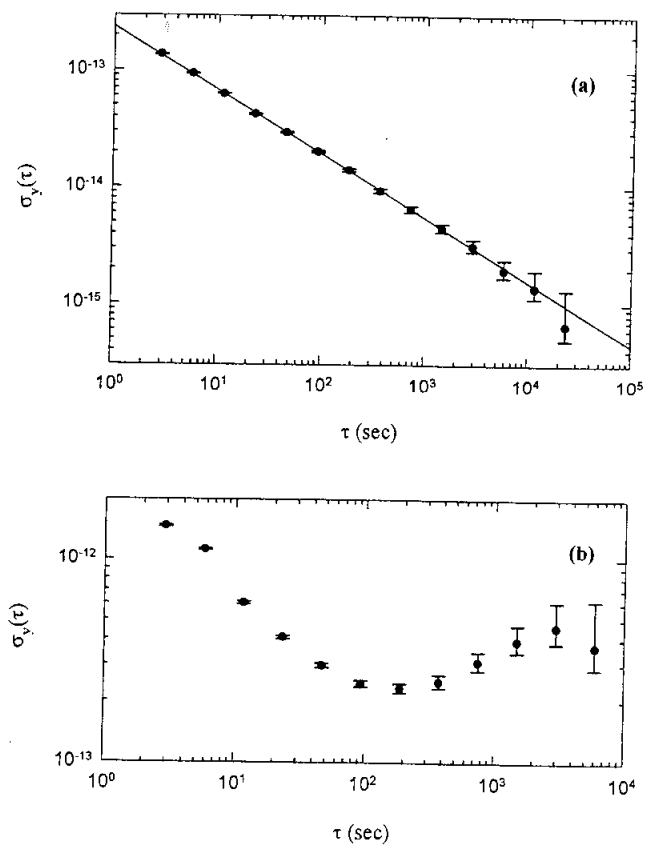

Figure 6. Allan deviations $\sigma_y(\tau)$ as a function of measurement time τ for the field-insensitive transition (a) and for the m=1 → m=1 field-sensitive transition (b). Line in (a) shows linear fit to all points except the last three. Data were taken with 12-cube beam delivery method.

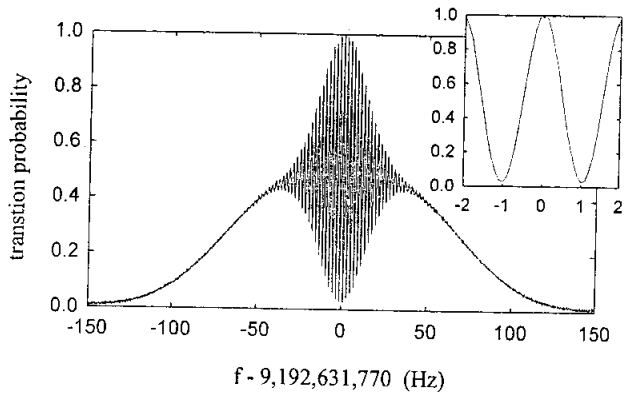

Figure 7. Ramsey fringes showing normalizedprobability of F=3, m=0 → F=4, m=0 transition as a function of microwave frequency f. Inset shows central fringes. Data were taken with 12-cube beam delivery method.

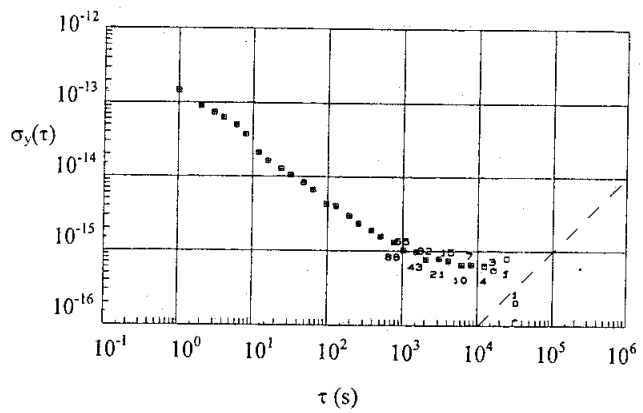

Figure 8. Allan deviations for LO maser as compared to another maser during the same time period covered by the data in Figure 6a.

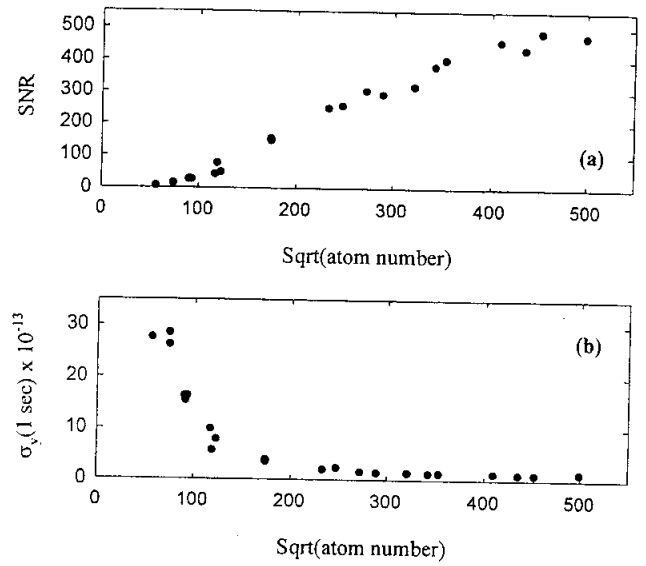

Figure 9. Signal to noise ratios (SNR) (a) and 1 second Allan deviations (σ_y (1 sec)) (b) for varying atom retum numbers. Data were taken with $\pi/4$ pulses using the 6-beam delivery method.

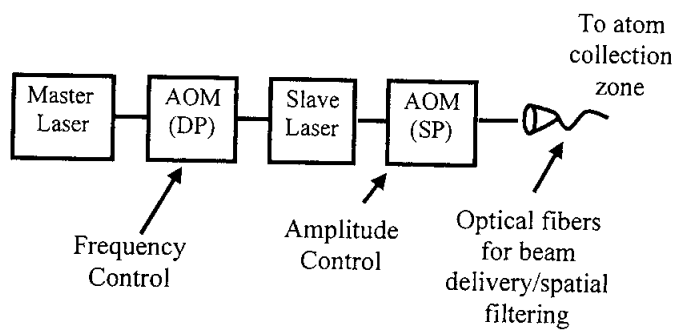

Figure 10. A master laser beam goes througha double pass (DP) AOM before injection locking a slave laser. Either the double pass or the single pass (SP) AOM can be used to attenuate the resonant light.

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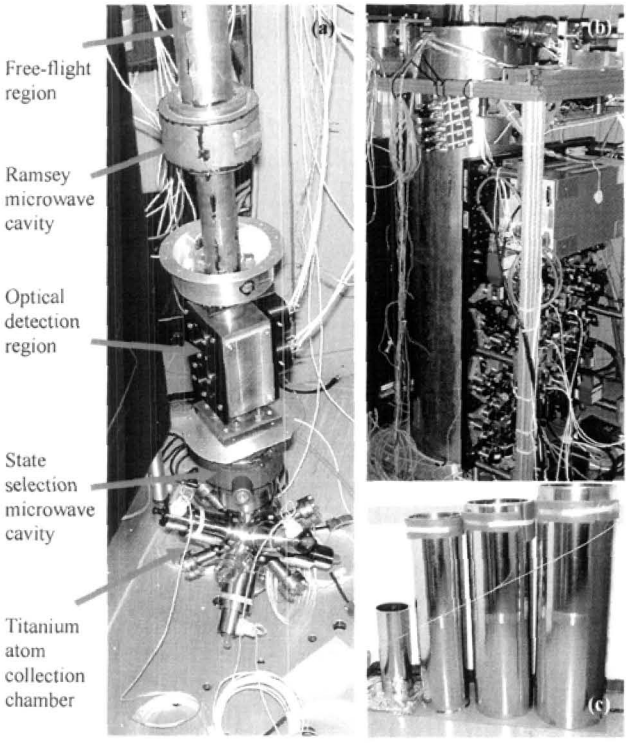
of cesium was loaded into the reservoir approximately two years ago. We tracked the cesium pressure (estimated from absorption measurements) in the atom collection chamber -- maintained at room temperature with no heaters or coolers -- to be 3 - 4 x 10^{-9} Torr over the first year, and have no indication that it has changed since.



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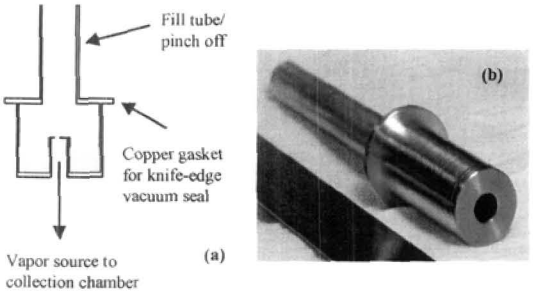

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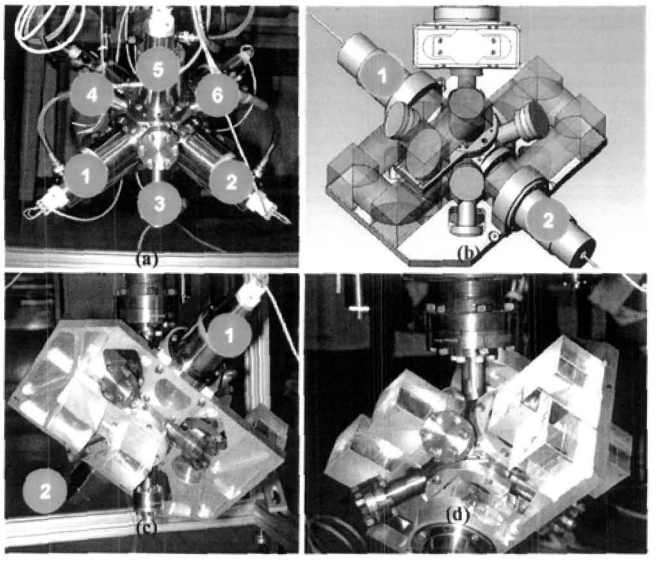

Figure 3. Beam delivery optics for traditional 6-beam configuration (a). Beam delivery optics for new 12-cube recirculation technique (b-d). Rendering in (b) shows optical beam-paths. Photographs in (c) and (d) show bottom and top view, respectively.

With our new recirculation technique, however, just two optical fibers are delivered to the physics package: one to generate the "up" beams, and one to generate the "down" beams. Each of these two fibers creates a beam which recirculates a total of three times through the atom collection region using transmission and reflection off of polarizing beamsplitter cubes, to recreate the familiar six lin-perp-lin beams. The order of the beams is such that within each pair of counter-propagating beams the power is balanced, while the power is reduced on each subsequent pass due to a small amount of absorption and reflection loss from the beamsplitter cubes. The recirculation optics are bolted onto the atom collection chamber, again, with no mechanical adjustability as shown in Figs. 3b-d. These optics consist of 12 polarizing beamsplitter cubes and three half-wave plates as shown from two orthogonal views in Fig. 4. In Fig. 4 as well as in Fig. 3b, orange traces the path of the "up" beam, and purple traces the path of the "down" beam. As mentioned previously, one of the four magnetic shields is removed to accommodate the recirculation optics.

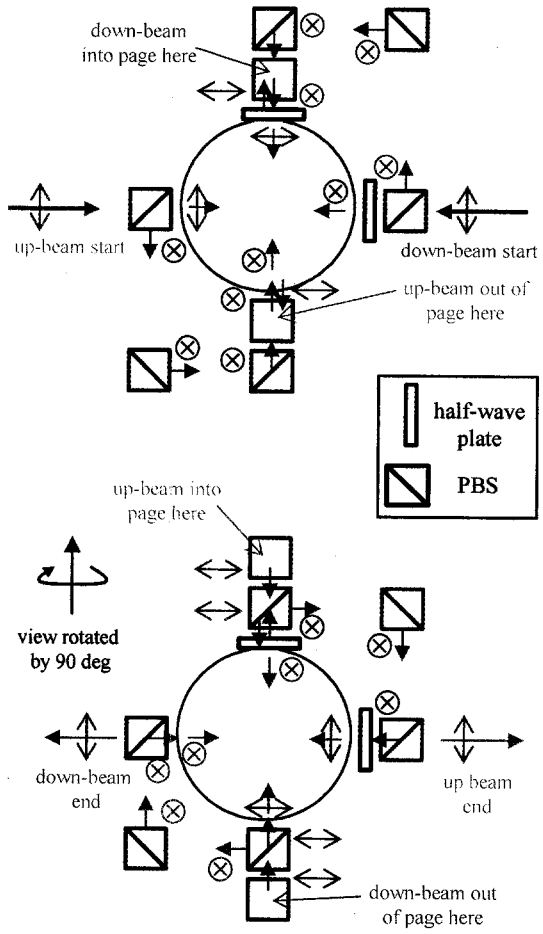

Figure 4. Two orthogonal views tracing beam paths of the "up" and "down" beams in the 12-cube optics apparatus. Single-ended arrows show beam direction, while double-ended arrows and circles with crosses show polarization. Lower drawing view is rotated by 90 deg about the vertical axis.

Since a single laser is typically used to generate the three "up" (or "down") beams in the traditional design, our new technique of recirculating one beam three times provides nearly three times more optical power than splitting the single beam into three and sending each independently to the collection area. This configuration allows trapping of the same number of atoms at lower total optical power, or alternately more atoms at the same power. In addition, this technique reduces the number of fiber couplings, fibers, and collimators from six to three (one "up" fiber, one "down" fiber, and a 3rd fiber for the "repumper" laser not discussed). It also uses fewer monitor photodiodes, and eliminates the difficulty of maintaining constant power ratios from one beam to the next within a triplet.

Before implementing this new recirculation technique, we tested the effect of potential beam imbalances introduced by common mode or differential optical power loss from one pass through the atom collection region to the next. Common mode power loss arises if both the "up" and "down" beams are attenuated by the same factor on each pass, for example by transmission loss through equal numbers of cubes or by absorption due to the cloud of cesium atoms. The use of an optical molasses with large optical beams keeps the absorption minimal for a given number of atoms in the cloud. This absorption was measured to be 2.6% per pass for the largest atom cloud we could load using the original 6-beam delivery technique, although if one uses more optical power with the recirculation technique, the absorption could be higher. Differential power loss arises if the "up" and "down" beams suffer different attenuations on each pass, for example if the polarizing beamsplitters have different losses, the half-wave plates have different transmission losses, or the half-wave plates are not rotated to the ideal angles.

Fig. 5a shows a measurement which simulates the expected repercussions of common mode loss in the "12-cube" technique, where the number of atoms successfully launched and returned to the detection area is plotted as a function of the percentage of light lost for each of the three passes through the atom collection region. These data were taken by launching atoms using the original 6-beam delivery method but adjusting the power of each pair of beams as needed, keeping each "up" beam still balanced with its corresponding "down" beam and keeping the total power constant. Fig. 5b shows the effect of differential power imbalances between one "up" beam and it's corresponding "down" beam, and Fig. 5c shows the same differential effect for all the "up" beams vs. all the "down" beams -- again keeping the total power constant.

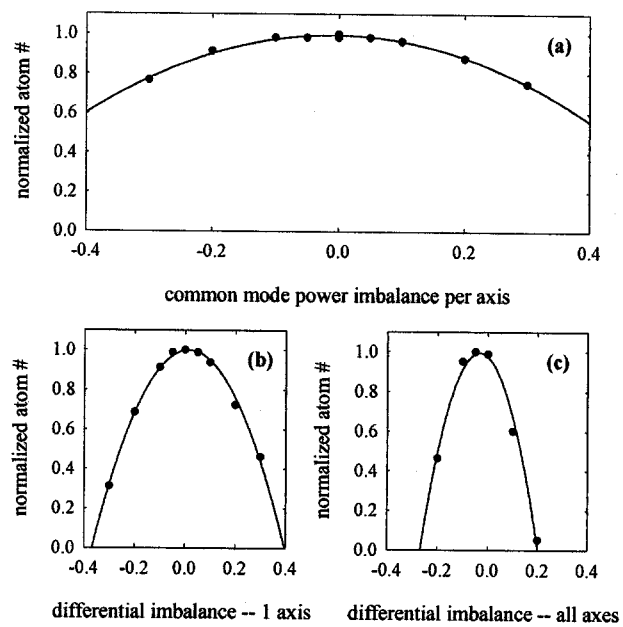

Figure 5. Atom return numbers for various types of power imbalances in the cooling/trapping beams. Common mode power imbalances in (a) are $(P_x - P_y)/P_{av}$ where P_x and P_y are the respective powers of either counter-propagating beam in 2 sequential axes, and P_{av} is the average power per beam. Differential power imbalances in (b) and (c) are $(P_x - P_{-x})/(P_x + P_{-x})$ where P_x and P_{-x} are the respective powers of 2 counter-propagating beams.

These measurements show that the atom return number does not vary by more then 10-20% for typical expected power imbalances < 10%. Indeed, in the next section we show that good fountain stability and performance has been achieved using this new recirculation technique. Higher atom numbers

were confirmed, however, higher atom temperatures also resulted: ~10 μK as opposed to the ~1 μK measured using the traditional 6-beam technique. Still, atom return numbers were approximately the same for the two techniques, because more atoms can be collected and launched with the new method. The high temperatures were not viewed as intrinsic to the recirculation technique based on the measurements shown in Fig. 5. It is plausible that the high temperatures were caused by misalignments of the resultant six beams because we affixed the polarizing beamsplitters to their mounting plates without trying to compensate for their steering imperfections and with a mounting system that clipped part of the beams (similarly for all beams though).

IV. FOUNTAIN PERFORMANCE

Fountain performance shown in Fig. 6a validates that the 12-cube recirculation technique can produce stability comparable to the traditional 6-beam technique. (See [2] for a review of recent fountains' operation and performance.) Atoms are launched at 4.1 m/s, state selected in the F=3, m=0 hyperfine level, and then exposed to a $\pi/2$ microwave pulse on their way up through the Ramsey cavity and on their way down. The free-flight time is ~0.5 s; microwaves in the Ramsey cavity are on resonance with the F=3, m=0 → F=4, m=0 transition at 9,192,631,770 Hz. Phase modulation is implemented by shifting the microwave phase at apogee either 90 deg or 270 deg on alternate launches. Return atoms are detected in both the F=3 and F=4 hyperfine states and normalized by the total detected. Frequency sensitivity is determined by fitting the slope of the central Ramsey fringe (Fig. 7). Allan deviations shown in Fig. 6a fit to the line 2.4 x $10^{-13}/\tau^{0.55}$ and reach 0.5 - 1.3 x 10^{-15} at 6.6 hours. Corresponding Allan deviations for the F=3, m=1 → F=4, m=1 magnetic field sensitive line are shown in Fig. 6b.

Microwaves are derived from mixing a 9.2 GHz DRO (dielectric resonant oscillator) signal with ~7.4 MHz from a synthesizer. The synthesizer and the DRO are locked to a LO maser signal distributed from a nearby building via a fiber-optic distribution assembly. The maser has a clean-up loop with a very stable crystal oscillator and typically has short-term stabilities near 1 x 10^{-13} at a second. Fig. 8 shows Allan deviations comparing this reference maser to another maser over the same time period in which the Fig. 6a data were taken.

In order to determine if our signal-to-noise ratio was shot-noise limited and also to deduce how much of the short-term instability was due to the LO, we took data that was *insensitive* to frequency fluctuations. This was done by eliminating the phase modulation and reducing the microwave power so that the atoms only experienced $\pi/4$ pulses rather than $\pi/2$ pulses; the microwaves were still resonant with the m=0 → m=0 transition. In this way, half the atoms still came back in the F=3 state, and half in the F= 4 state. This technique is in common use. Typical one second Allan deviations were 1.4 x 10^{-13}, so assuming the LO noise adds in quadrature, it contributed ~2 x 10^{-13} to the one second Allan deviation in Fig. 6a's data. This is consistent with expectations from the maser instability when taking into account LO aliasing (the Dick effect) [3]. Fig. 9 shows one second Allan deviations and corresponding SNRs measured in the same way -- with $\pi/4$ pulses -- but varying the number of launched atoms. Fig. 9a shows the expected dependence of the SNR varying linearly with the square root of atom return number, and that the fountain data are shot-noise limited up to SNRs ~ 500.

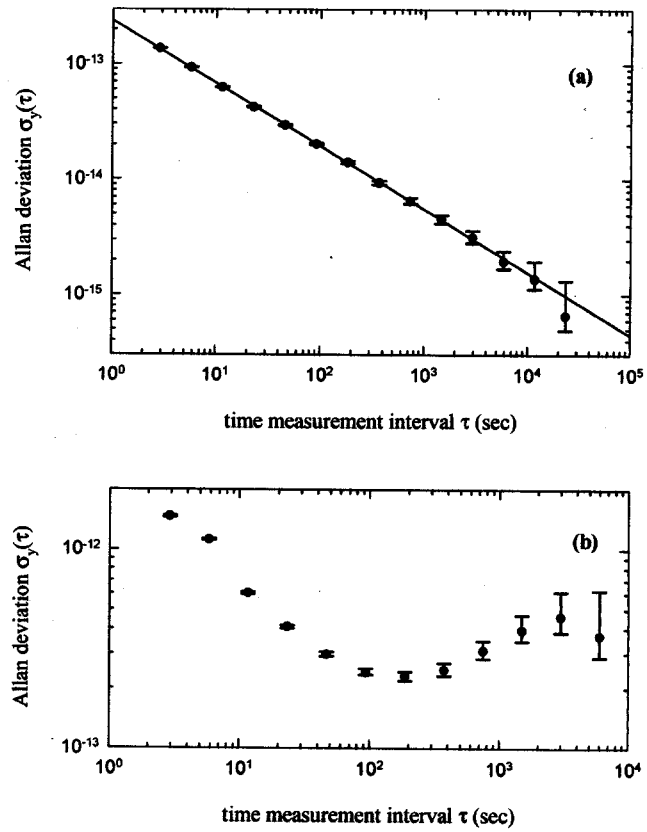

Figure 6. Allan deviations $\sigma_y(\tau)$ as a function of measurement time τ for the field-insensitive transition (a) and for the m=1 → m=1 field-sensitive transition (b). Line in (a) shows linear fit to all points except the last three. Data were taken with the 12-cube beam delivery method.

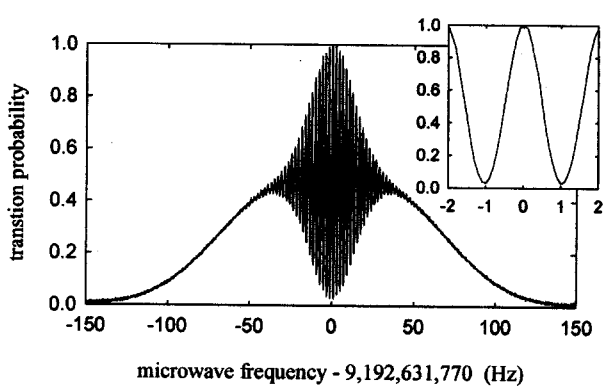

Figure 7. Ramsey fringes showing normalized probability of F=3, m=0 → F=4, m=0 transition as a function of microwave frequency. Inset shows central fringes. Data were taken with 12-cube beam delivery method. The rapid loss of fringe contrast, also present in the 6-beam data, is unexpected for these atom temperatures (~10 and 1 μK respectively).

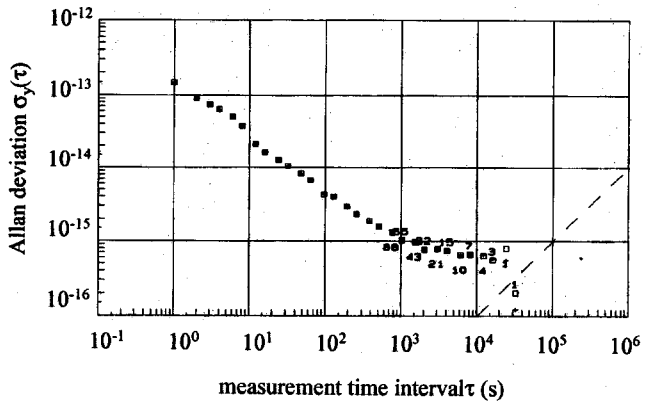

Figure 8. Allan deviations for LO maser as compared to another maser during the same time period covered by the data in Figure 6a.

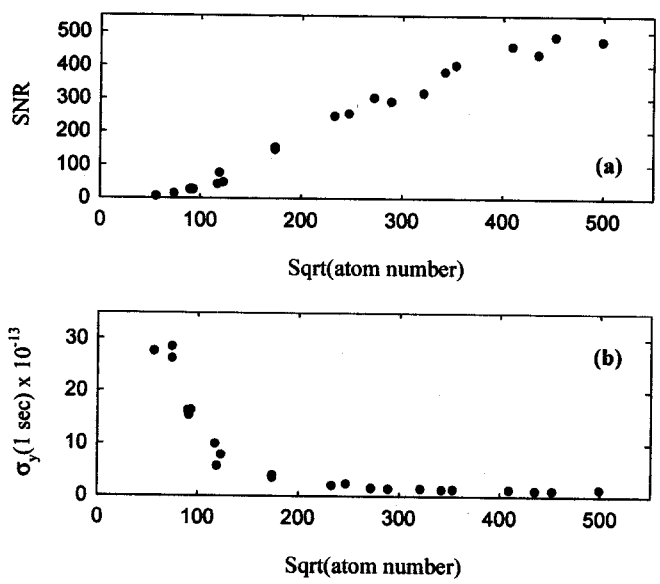

Figure 9. Signal-to-noise ratios (SNR) (a) and 1 second Allan deviations (σ_y at 1 sec) (b) for varying atom return numbers. Data were taken with $\pi/4$ pulses using the 6-beam delivery method and a launch velocity of 4.3 m/s.

V. Mitigation of Light Shift Without Mechanical Shutters

Several years ago we proposed operating the fountain without mechanical laser shutters while keeping the light shift below 10^{-17} [4]. In this proposed technique, light intensity is reduced during the free-flight time using a single pass (SP) AOM (acousto-optic modulator), and the light shift is further reduced by causing slave lasers to run off resonance using a double pass (DP) AOM as shown in the Fig. 10. We have now verified this works down to the 2×10^{-15} level, limited only by statistics. Table I shows the relative light shifts for various combinations of attenuation as compared to the configuration in which light is attenuated with both a single and a double pass AOM. The table shows that using just the SP or just the DP gives > 10^4 reduction in absolute light shift, thus using both SP and DP, we would expect > 10^8 reduction in light shift. Better limits will be attainable after collecting more data.

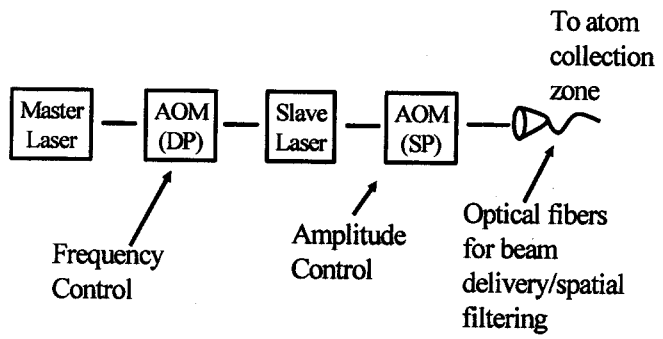

Figure 10. A master laser beam goes through a double pass (DP) AOM before injection locking a slave laser. Either the double pass or the single pass (SP) AOM can be used to attenuate the resonant light.

TABLE I. MEASURED LIGHT SHIFTS

Attenuation Configuration	Fractional Frequency Shift (relative to SP+DP)
NO attenuation (i.e. full light shift)	2×10^{-11}
Just Single Pass AOM	$< 2 \times 10^{-15}$
Just Double Pass AOM	$< 2 \times 10^{-15}$
Mechanical Shutters and Single and Double Pass AOM	$< 4 \times 10^{-15}$

Conclusion

This fountain, built to aid in the design and implementation of the PARCS flight design, has demonstrated good stability using a new recirculation technique for beam delivery. In addition, the traditional 6-beam technique, as implemented with no mechanical adjustments on the physics package, has produced low temperatures and shot-noise limited performance up to SNRs ~ 500.

Lastly, we validated a new technique for reducing light shift at the 10^4 level using a DP AOM injection locking a slave laser. Longer sets of data should be taken to confirm that this method can eliminate the need for shutters.

Acknowledgment

As a testbed for the PARCS experiment this work benefited from contributions by many of the PARCS team members. Command and control with traceability to the flight system were implemented by a team at JPL including Steve Cole, Brian Franklin, Tom Garvey, Richard Guerrero, Vahag Karayan, Erik Peterson, Phil Yates, and George Wells. Electronics support included contributions by Ted Ozawa, Tom Radey, and Rudy Vargas, from JPL. John White provided considerable laboratory support. The microwave cavities were built by Steve Jefferts at NIST. Eric Burt from JPL performed the passive shielding effectiveness measurement.

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