Rubidium-based Atomic Clock

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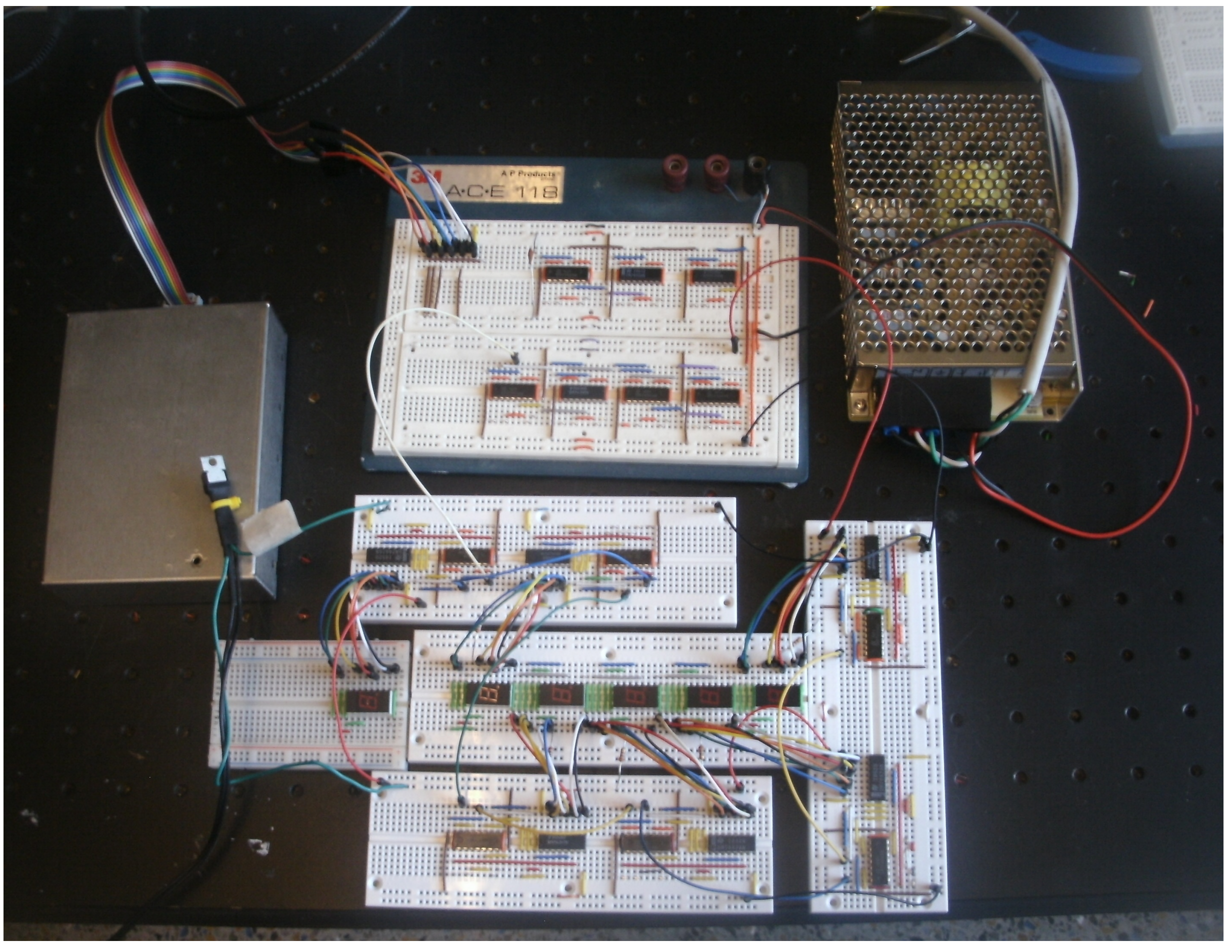

Contents

1 Introduction

An atomic clock is defined simply as a clock that bases its time keeping "on an electrical oscillator regulated by the natural vibration frequencies of an atomic system [1]" rather than an astrological phenomenon such as a solar day. They have historically been made using many different elements including quartz, ammonia, hydrogen, rubidium, and cesium [2]. All the clocks work on the basis of counting oscillations.

The second successful atomic clock, after the inaccurate ammonia clock built in the USA, was made at the National Physical Laboratory in Teddington in 1955 by Louis Essen. The clock was dubbed Caesium I and was the first of its kind to be significantly more accurate than clocks based on the rotation of the earth, such as pendulums [2]. Within ten years Essen increased the accuracy of the clock to 1 second in 2000 years and redefined the second "as the time taken for 9192631770 cycles of the radiation corresponding to the hyperfine transition of the ground state of caesium-133 [2]". Today, the second is still defined as such. Since then, cesium clocks have been dubbed as the first standard. Until the invention of the quantum logic clock, they were the most accurate clocks scientists could build.

Rubidium is the secondary standard when it comes to atomic clocks. While not as accurate as cesium clocks, they are less expensive, smaller, and more reliable [12]. Rubidium clocks are used in many applications, possibly the most notable of which is their presence on satellites. The atomic clocks on satellites are a primary factor in GPS navigation, which have applications for farming and surveying [6, 10]. There are also experiments using rubidium clocks such as NASA's RACE.

The construction of an atomic clock can be split into three stages - managing the input frequency from the generator and converting it into a square wave, stepping it down to a 1 Hz oscillation, and displaying it. It is possible to build an atomic clock completely from scratch but it is much easier and faster to begin with a preassembled function generator.

In this paper we will explore the process of building an atomic clock from a function generator, go into an in-depth introductory discussion of the Datum LPRO, and examine how rubidium function generators work.

2 Building an Atomic Clock

When building the atomic clock, we chose to start with a function generator that gave us an output of a 10 MHZ sine wave. There are three stages from this point described in the following sub-sections and a fourth outlining the power supply to be used.

2.1 Division Circuit

To get the frequency down to 1Hz we ran it through seven decade counters as shown in Figures 1 and 2. The way the 7490 works is when the chip receives a pulse it begins to count using 4-bit binary numbers. Figure 3 shows a diagram of the inside of a 7490. When the logic results in 1001 it sends an output pulse. To get the 10MHz down to a 1Hz pulse we divided it by 10, seven times.

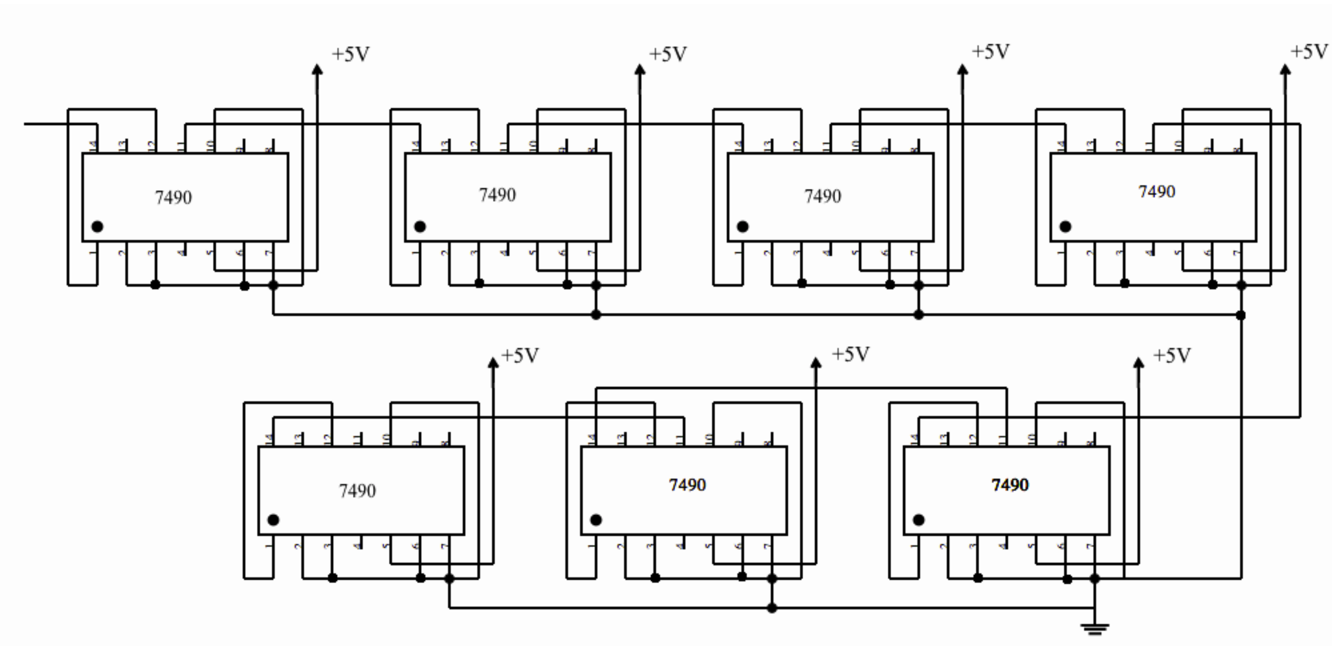

Figure 1: A schematic showing the seven 7490 decade counters.

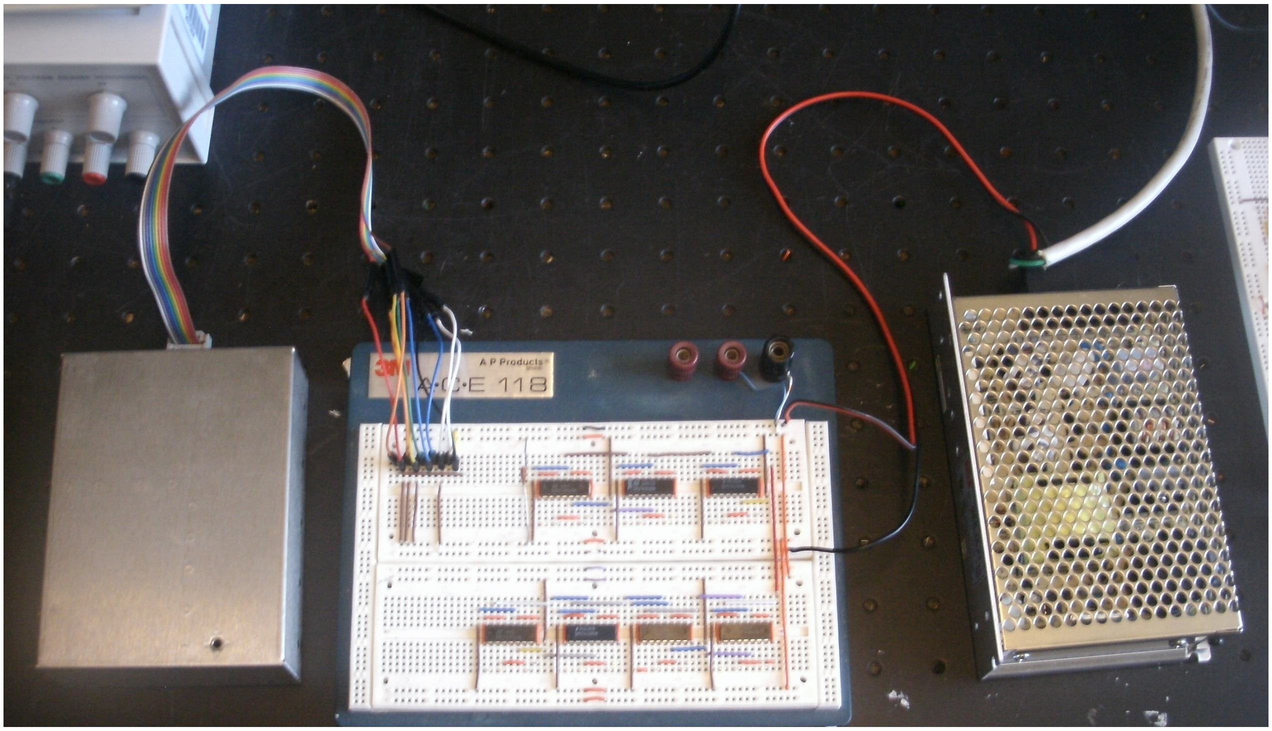

Figure 2: A photo showing the seven decade counters arranged in the breadboard with the function generator visible to the left and the power supply for the function generator shown to the right.

2.2 Display Circuit

The second step we completed was creating a display. The display can also be split into three components - the 7490, 7447, and 7-segment LED. The 7490 serves a similar purpose as dividing down the frequency. For our display, we had six sets of components linked together so that when the first 7490 counted to 9, the second would count to 1 and so on until the point when the display would read 999999 and then start again at 0. The 7490 sends signals in batches of 10 to the 7447, starting at 1 and ending at 0. The 7447 interprets the last signal sent as 0 (or 10 as we would see it). Essentially, we just kept reducing the frequency by 10Hz but checked the frequency after each division.

The purpose of the 7447 is to count pulses from the 7490 and send highs to the correct component LEDs of the 7-segment display. A high indicates that segment of the display should be turned on. Figure 4 shows a diagram of the inside of a 7447. As shown in the schematic in Figure 5, the 7447 receives four inputs from the 7490. It uses them to decode

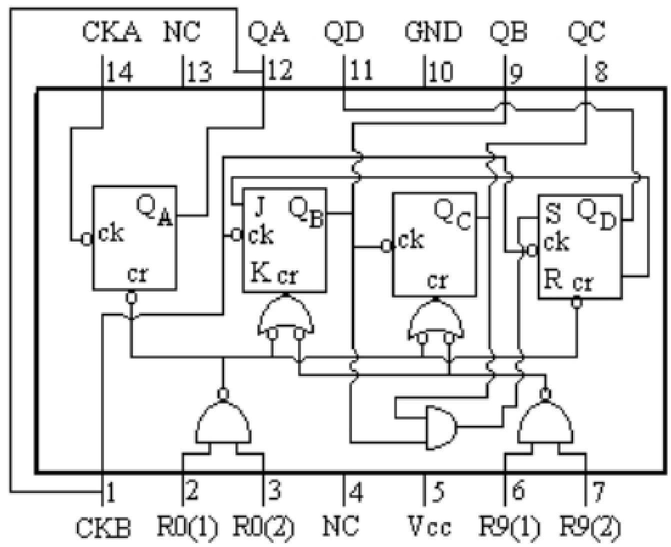

Figure 3: A diagram illustrating the inside of a 7490 and the logic used to count up to 9 in 4-bit binary [7].

which LEDs should light. A table of the logic used by the 7447 is shown in Figure 6. For example, when pin 7 receives a high from the 7490, it causes segments b and c to light up.

The final component of the display is, of course, the display. The 7-segment LED is comprised of 11 pins and 7 LEDs. The schematic of the connections between all three components and a photo of the whole apparatus are shown in Figures 5 and 7. The 7-segment receives its power through a resistor connected to pins 3 and 14 and connects to the ground through the 7447. It does not directly connect to the ground. Each segment is connected independently to pins 9-15 of the 7447.

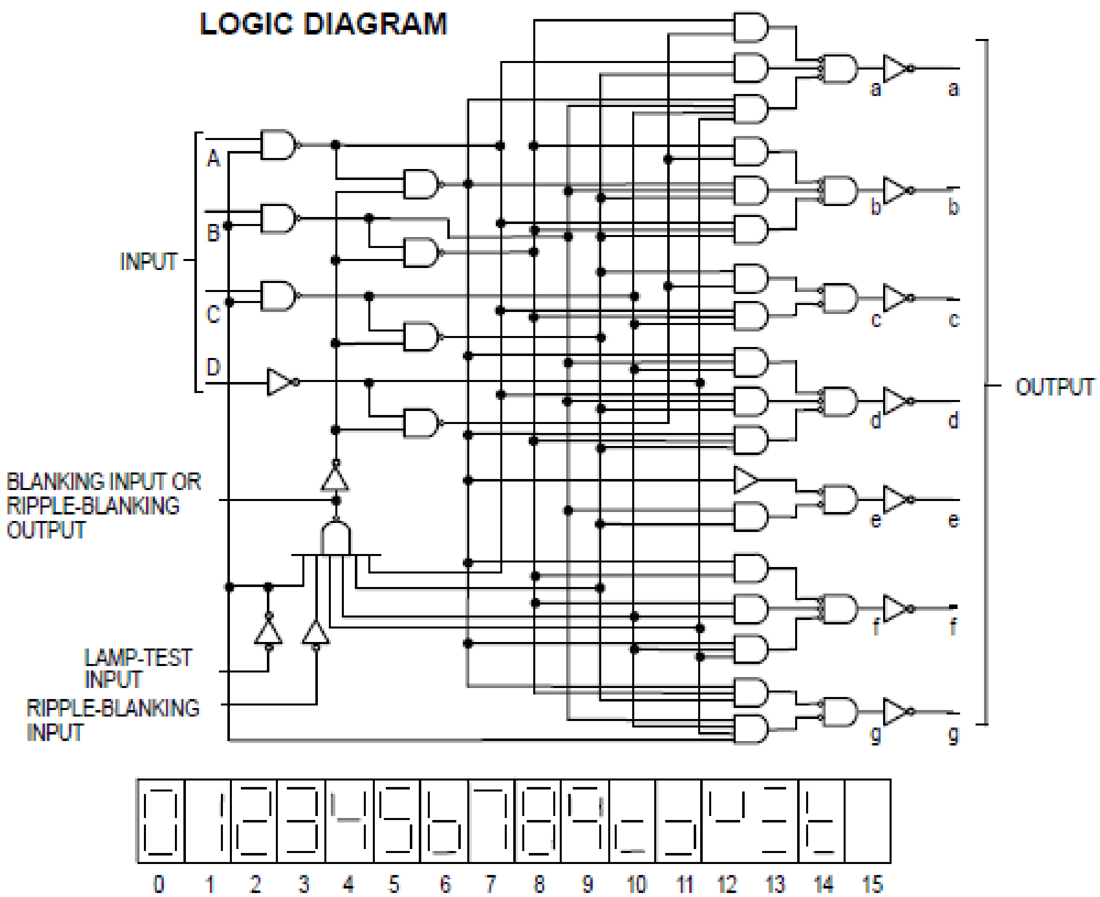

Figure 4: A diagram illustrating the inside of a 7447 and the logic used to count and send signals to the 7-segment LED [3].

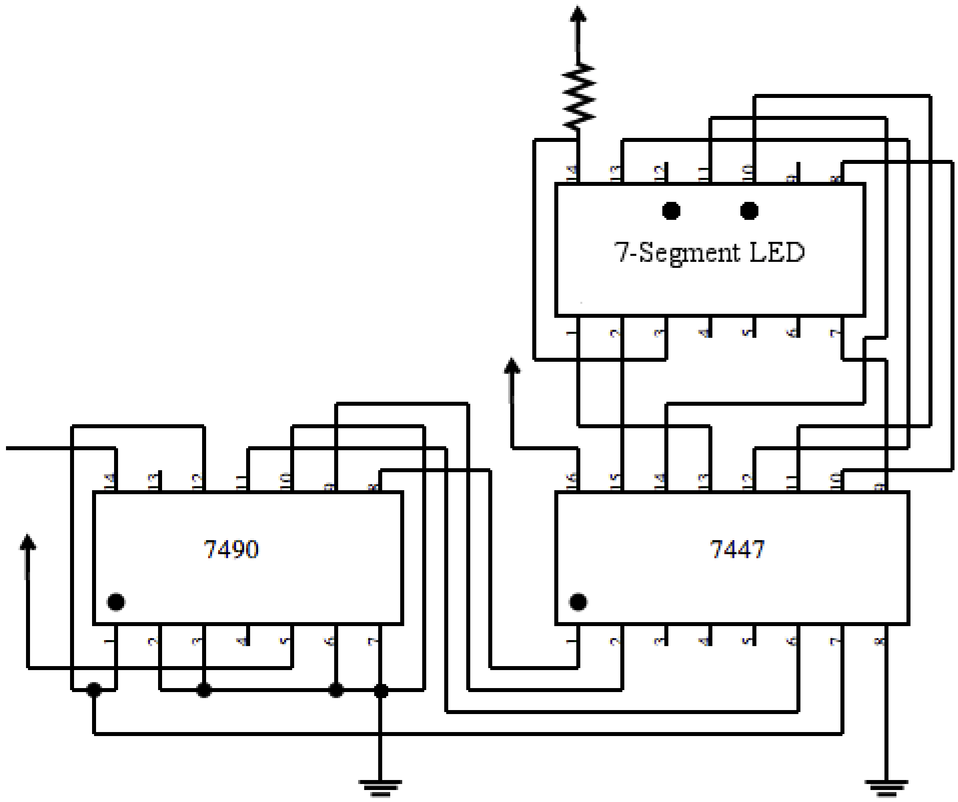

Figure 5: A schematic showing a single 7-segment LED display. A total of six of these were used for the display. The output from pin 11 on the 7490 is also connected to pin 14 of the successive 7490 such that when the first reaches 9, the second will count 1, and so on.

Inputs							Outputs							
D	**C**	**B**	**A**	$\overline{BI}/\overline{RBO}$	$\overline{RBI}$	$\overline{LT}$	$\bar{a}$	$\bar{b}$	$\bar{c}$	$\bar{d}$	$\bar{e}$	$\bar{f}$	$\bar{g}$	**Display**
0	0	0	0	1	1	1	0	0	0	0	0	0	1	
0	0	0	1	1	1	1	1	0	0	1	1	1	1	
0	0	1	0	1	1	1	0	0	1	0	0	1	0	
0	0	1	1	1	1	1	0	0	0	0	1	1	0	
0	1	0	0	1	1	1	1	0	0	1	1	0	0	
0	1	0	1	1	1	1	0	1	0	0	1	0	0	
0	1	1	0	1	1	1	1	1	0	0	0	0	0	
0	1	1	1	1	1	1	0	0	0	1	1	1	1	
1	0	0	0	1	1	1	0	0	0	0	0	0	0	
1	0	0	1	1	1	1	0	0	0	1	1	0	0	
1	0	1	0	1	1	1	1	1	1	0	0	1	0	
1	0	1	1	1	1	1	1	1	0	0	1	1	0	
1	1	0	0	1	1	1	1	0	1	1	1	0	0	
1	1	0	1	1	1	1	0	1	1	0	1	0	0	
1	1	1	0	1	1	1	1	1	1	0	0	0	0	
1	1	1	1	1	1	1	1	1	1	1	1	1	1	

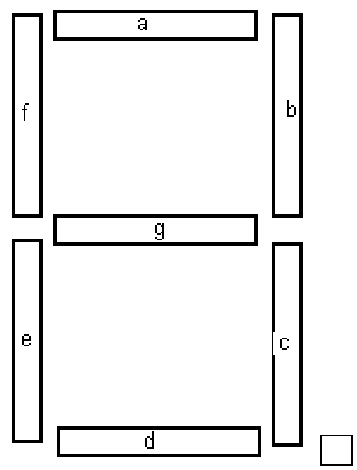

Figure 6: A table of the logic used inside the 7447 to determine which component LEDs should be lit up [9].

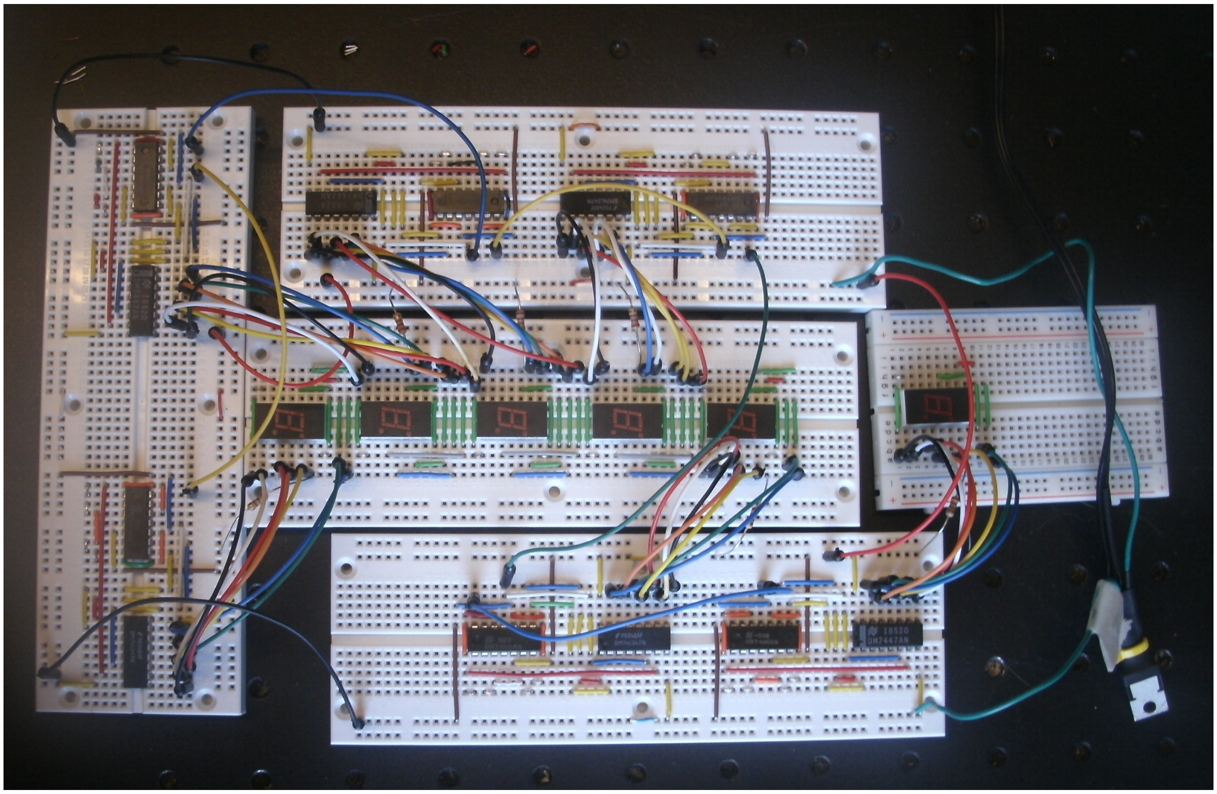

Figure 7: A photo showing the six seven-segment LEDs and their corresponding 7490s and 7447s. Having the six LEDs displayed without covering them in wires posed a unique problem that was surmounted by arranging the processors around the central LED-board.

2.3 Conversion Circuit

For our setup we needed to convert the sine wave output by the function generator into a square wave to feed into the decade counters. This posed to be an insurmountable problem in our time limit. We tried numerous chips and circuit designs but all failed.

The LM311 and Field Effect Transistor in Figures 8 and 9 both failed at high frequencies. At 100kHz and lower, both circuits could successfully convert a sine wave into a square wave. Higher frequencies than that and the wave became a distorted sine wave. For the transistor circuit we replaced the voltage divider with a potentiometer but were still unable to achieve square waves at higher frequencies.

Both the LT1016 and 7414 circuits shown in Figures 10 and 11 were recommended by the LPRO instruction manual. However, both circuits simply reduced the input signal from the function generator to an unusable level. We tried the complete circuits as shown

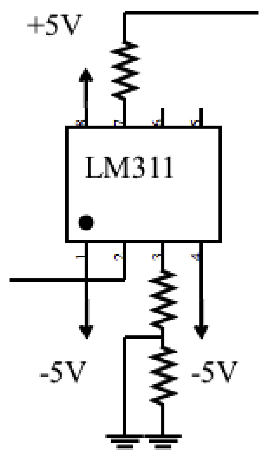

Figure 8: A schematic showing the setup of the LM311 with the input on pin 2 and the output on pin 7. Rather than having a potential between +5V and ground, it also had to be connected to a -5V source.

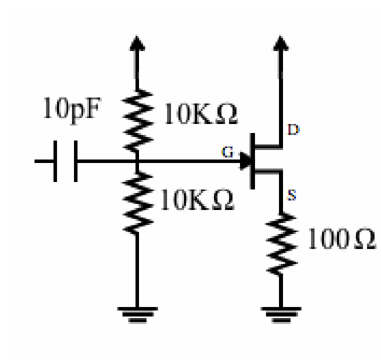

Figure 9: A schematic showing the field-effect transistor. All it needed was a voltage divider but unfortunately it just reduced the input signal to an unusable level.

in the manual and simplified versions; both of which failed when paired with the function generator itself. We suspect the generator could not drive the signal through the circuit as the same effect occurred with less powerful multi-use lab function generators.

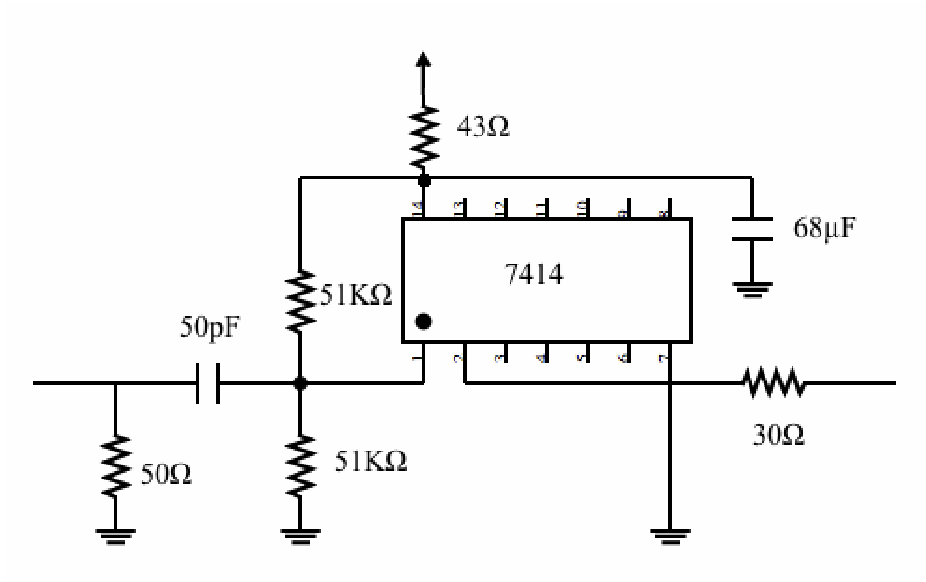

Figure 10: A schematic showing the setup of the 7414. We also tried this circuit without the first resistor and capacitor on the left.

Finally, we tried the very simple approach shown in Figure 12. The 4009 is a CMOS logic chip that would have possibly caused issues sending information to the decade counters if it had worked. Like the LT1016 and 7414 it killed the signal. A photo of the complete setup, excluding a conversion circuit, is shown in Figure 13.

2.4 Power Supply

Our original intention for supplying power to the division, display, and conversion circuits was to modify an AC to DC wall wart with wires to fit into the breadboard. The modification was successful with the wall wart supplying a constant +5V. However, the converter caused a large amount of noise as shown in the Figures in 5. Also included in 5 are the specifications for the wall wart we used. Using a variable power supply with its own internal AC to DC conversion produced the much cleaner division circuit outputs shown in 6.

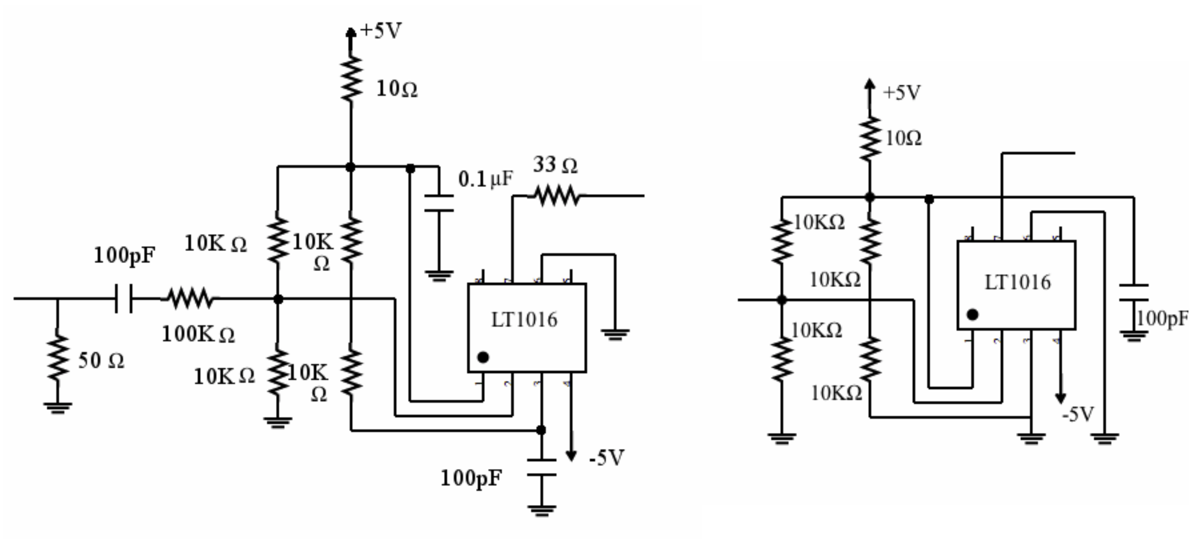

Figure 11: A schematic showing the complete setup of the LT1016 on the left and a simpler version on the right. This setup required two voltage dividers with the output on pin 7.

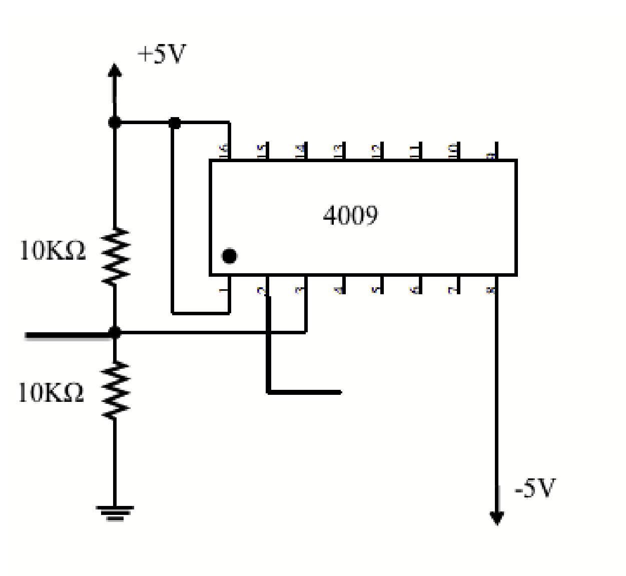

Figure 12: A schematic showing the setup of the 4009 CMOS logic chip. All it required was a voltage divider and a +5V/-5V power supply. The input is on pin 3 and the output on pin 2.

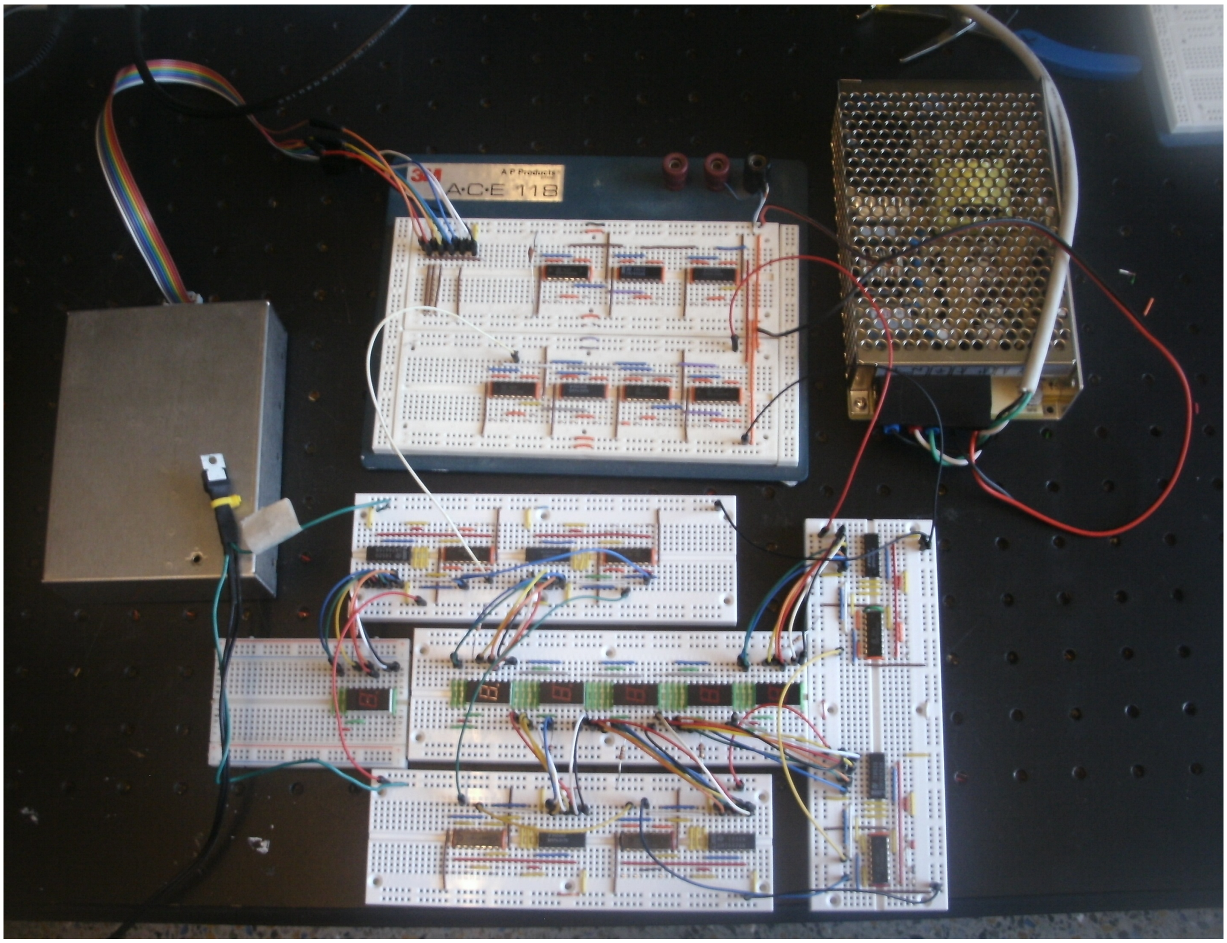

Figure 13: A photo showing the entire apparatus. The function generator is shown to the far left and its power source to far right. Center top is the division circuit and center bottom is the display.

3 The Datum LPRO and Rubidium Function Generators

3.1 Datum LPRO

Before we go into the basic fundamentals of how rubidium function generators operate, we will give an introduction to the generator we used. The Datum LPRO is a rubidium atomic frequency standard function generator. It is designed for a use-life of 10 years without maintenance and thus is often used on GPS and communications satellites.

The LPRO uses a 20 MHz voltage-controlled crystal operator to generate it's atomic frequency, the exact process of which we will discuss later in this section. The signal directly generated by atomic activities is weak so it is fed through a servo that converts the "current into a voltage, then amplifies, demodulates, and integrates it for high dc servo loop gain [8]." The output is cut in half and directed through a buffer before being modulated to microwave frequency. Finally, the rubidium frequency of 6.8346875 GHz is extracted by the high Q resonator. High Q in this instance being approximately 10^7, which produces a stable oscillation close to the natural frequency [11]. Figure 14 sums up the explanation in a diagram from the LPRO use manual.

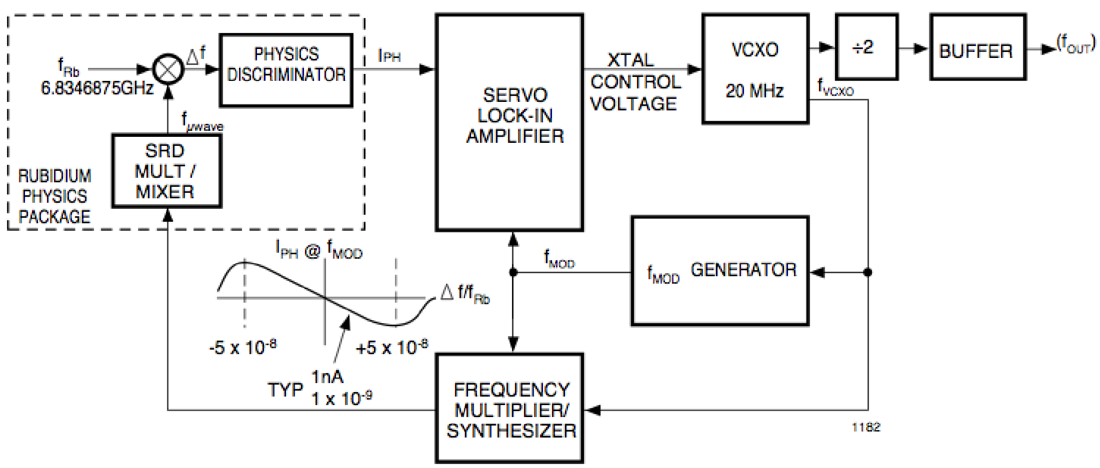

Figure 14: A diagram of the inside of the LPRO taken from the use manual [8].

Figure 15 shows the recommended hookup for optimal operating conditions. The LPRO requires a 24 V power supply and return, a device for monitoring the warm-up period (J1-6 and J1-4), and the device for which the generator is required (J1-1 and J1-2), in our case a clock. The output of each pin is listed in Table 1 [8]. Figure 16 shows an oscilloscope trace taken of output from the function generator.

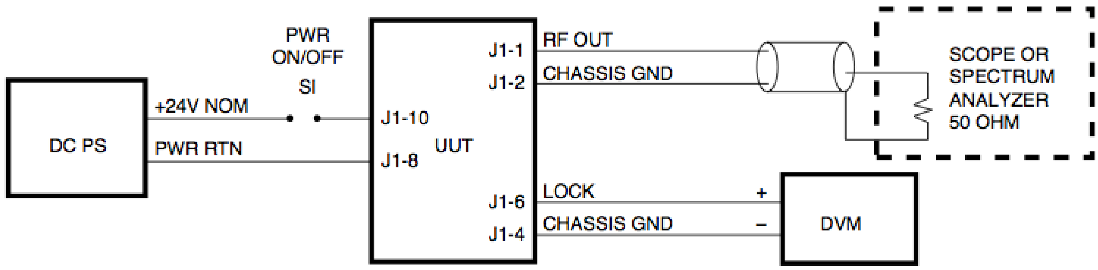

Figure 15: A diagram of the intended hookup of the LPRO taken from the use manual [8].

Wire Color	Pin Number	Signal
Brown	1	10MHz sine out
Red	2	Common Ground
Orange	3	Common Ground
Yellow	4	Common Ground
Green	5	Voltmeter
Blue	6	Unlock indicator
Purple	7	Frequency control
Gray	8	24V Ground
White	9	Voltmeter
Black	10	+24V power in

Table 1: A table of the pin hookups for the LPRO. [8]

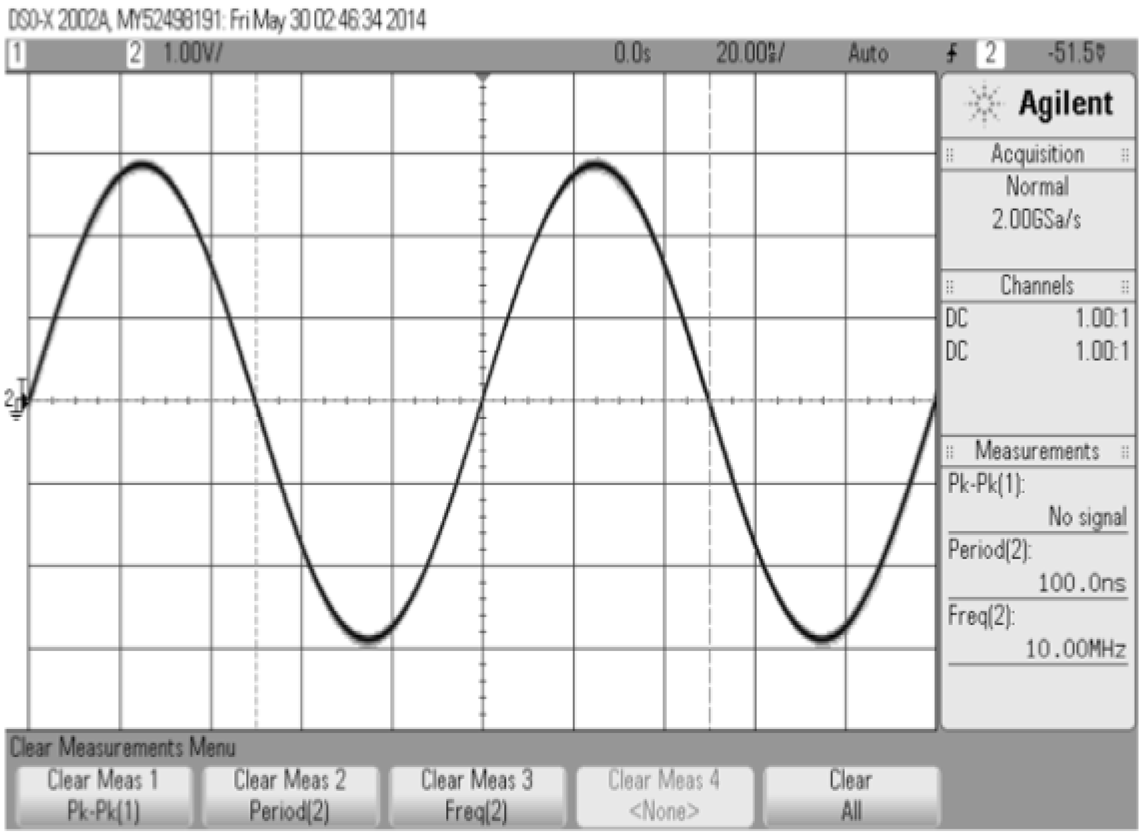

Figure 16: An oscilloscope trace of the function generator output.

3.2 Rubidium Function Generator

The process of producing the frequency used for our clock is the same process used in all vapor-cell atomic clocks. “A microwave signal is derived from a 20 MHz voltage-controlled crystal oscillator (VCXO) [8]” and is sent “through a vapor of rubidium atoms housed in a glass cell and is detected by a photodiode [4].” The signal output from the crystal is stepped up to a frequency near 6.8347 GHz. The microwaves, after being carefully tuned to the exact frequency, cause a transition in the hyperfine ground state levels of ^{87}Rb.

Like building the necessary circuitry and display for the clock, achieving the desired output frequency can split into three physical portions, a lamp, filter cell, and resonance cell. The purpose of the ^{87}Rb discharge lamp is optical pumping. A ^{87}Rb vapor filter cell aids in the same process. Finally, the resonance cell, filled with ^{87}Rb and other gasses emits the hyperfine transition frequency.

To achieve the transition between hyperfine states a population inversion must be created. The lamp light connects the hyperfine excited states to the hyperfine ground states. The filter cell removes the component shown in Figure 17 labeled *a* leaving only the one transition. Another purpose of the lamp is to indicate if the microwaves are the correct frequency. When they are not accurate, there is no population inversion and all lamp light passes through the cells unabsorbed.

Inside the resonance cell resides a vapor of ^{87}Rb and typically nitrogen and a noble gas [4]. The buffer gas serves three purposes. It eliminates Doppler broadening due to the collisions between the buffer gas and the ^{87}Rb atoms. With some physics beyond the scope of this paper, it protects the precious ^{87}Rb atoms from coming into contact with the glass walls of the cell and only weakly affects the state of the atom. Finally, it aids in the optical pumping by not allowing the ^{87}Rb atoms to reabsorb their own photons [4].

All of the above is used to achieve a lock on the frequency of the hyperfine phase transition. Once the lock is achieved, the output frequency can be used for the desired purpose. While in operation the frequency is continuously monitored for accuracy.

4 Conclusion

Rubidium atomic clocks have many uses in our everyday lives from providing us with GPS and satellite television and internet service to more efficient farming practices and lower food costs [10, 8]. Being a secondary standard they are equipped for all but the most precise measurements and live up to a high standard of quality. Building a clock from a rubidium function generator poses many challenges, all but one of which we were able to surpass. The logic of the division and display circuits was sound and can be seen demonstrated in 7. The conversion circuit suffered from the inability of the function generator to drive the circuit. Despite the conversion circuit the project of better understanding circuits and the inner workings of rubidium function generators is still a success.

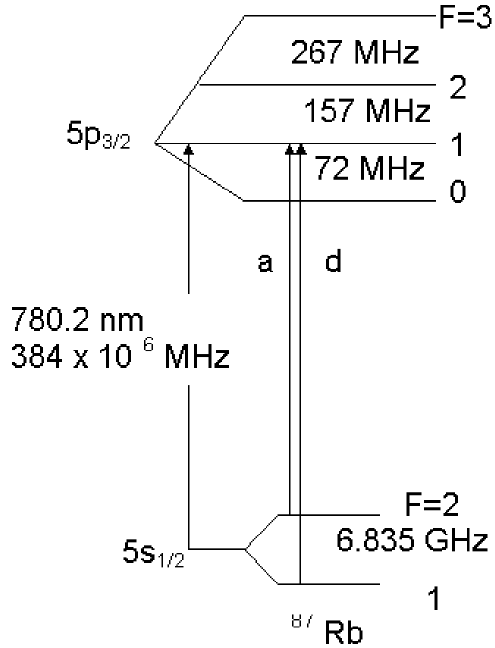

Figure 17: A diagram of the hyperfine states of ^{87}Rb, not to scale [5]. The image was modified to show only the relevant information.

5 Appendix A

Wall wart specs:

- Texas Instruments AC Adapter AC-9175
- Model: SAC A30650
- Class 2 Transformer
- Input: 120V 60Hz 7W
- Output: 6VDC 500mA

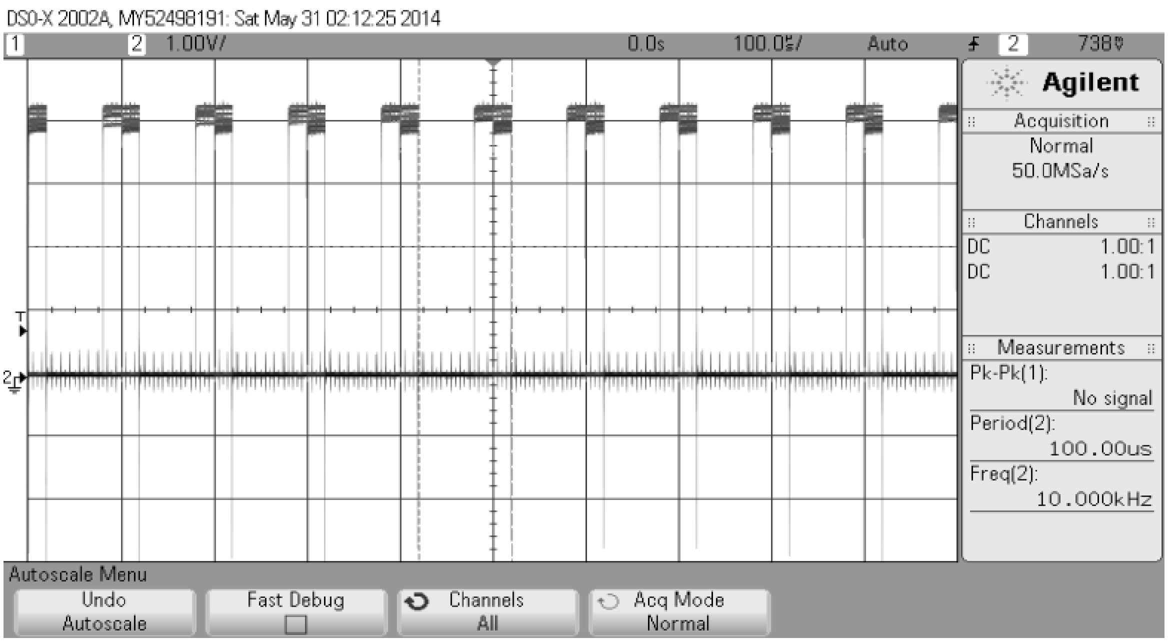

Figure 18: An oscilloscope trace of the output from one decade counter, with an input square wave of frequency 100kHz, being supplied power from the wall wart. Note the division is still correctly functioning despite the noise.

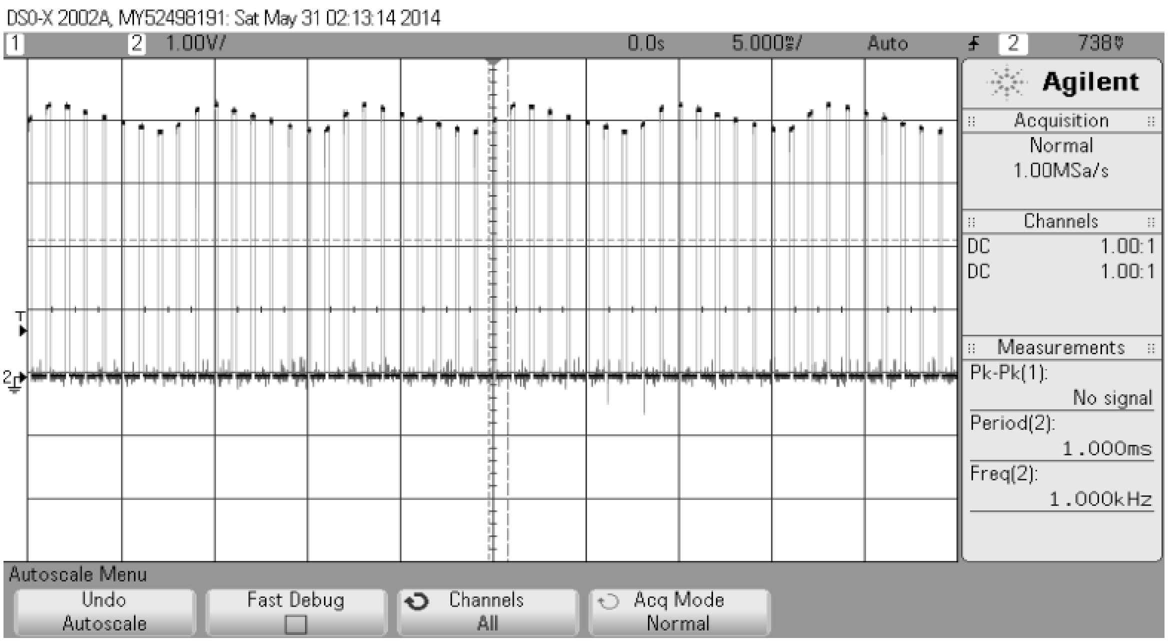

Figure 19: An oscilloscope trace of the output from two decade counters, with an input square wave of frequency 100kHz, being supplied power from the wall wart. The noise was cleared up slightly but has transferred to show a remnant of the AC supply. This trace was zoomed out to show the sinusoidal effect. Note the division is still correctly functioning.

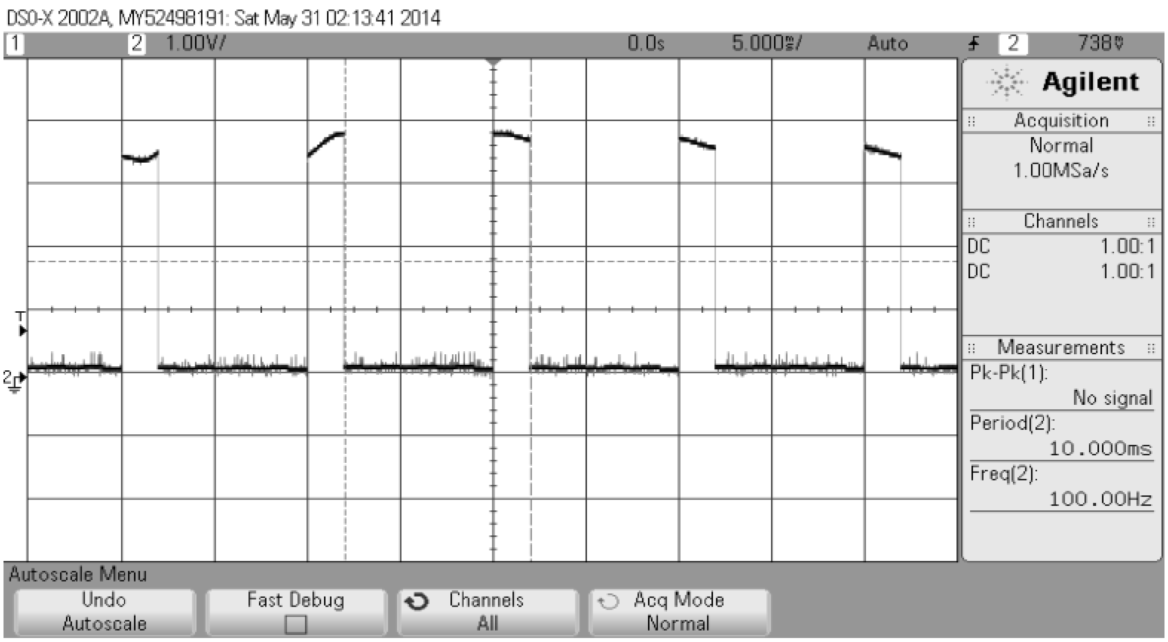

Figure 20: An oscilloscope trace of the output from three decade counters, with an input square wave of frequency 100kHz, being supplied power from the wall wart. The trace has been zoomed in to show the instability of each square pulse caused by the power supply. Note the division is still correctly functioning.

6 Appendix B

Note that the function generator used for the testing of the division circuit could produce a square wave at a maximum frequency of 100kHz. Frequencies higher than 100kHz reduced to sinusoidal, noisy waves that could not be interpreted by the decade counters.

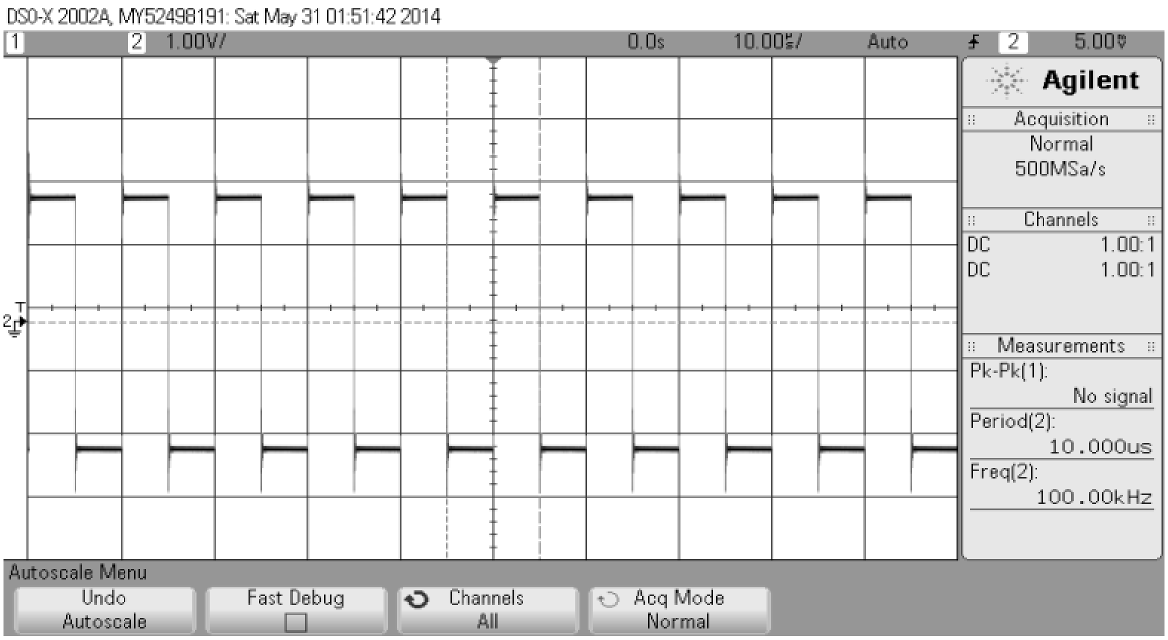

Figure 21: An oscilloscope trace of the 100kHz square wave directly from a lab function generator used to test the division circuit.

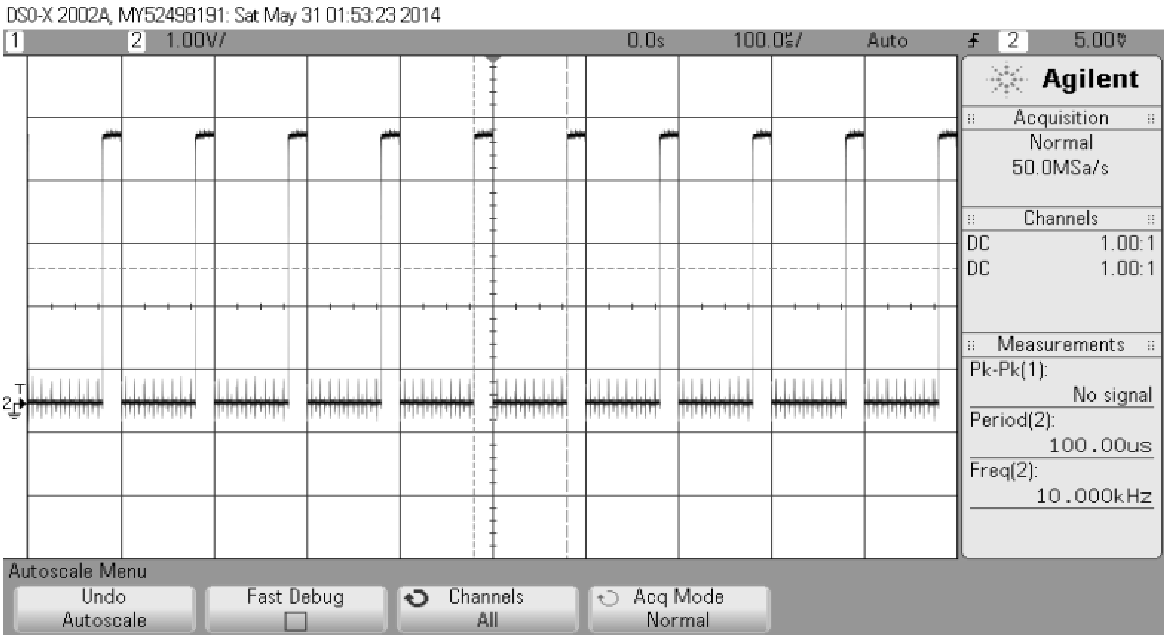

Figure 22: An oscilloscope trace of the 100kHz square wave passing through one decade counter. Notice the frequency has decreased by a factor of 10Hz and the separation increased by a factor of 10 to display the same number of pulses.

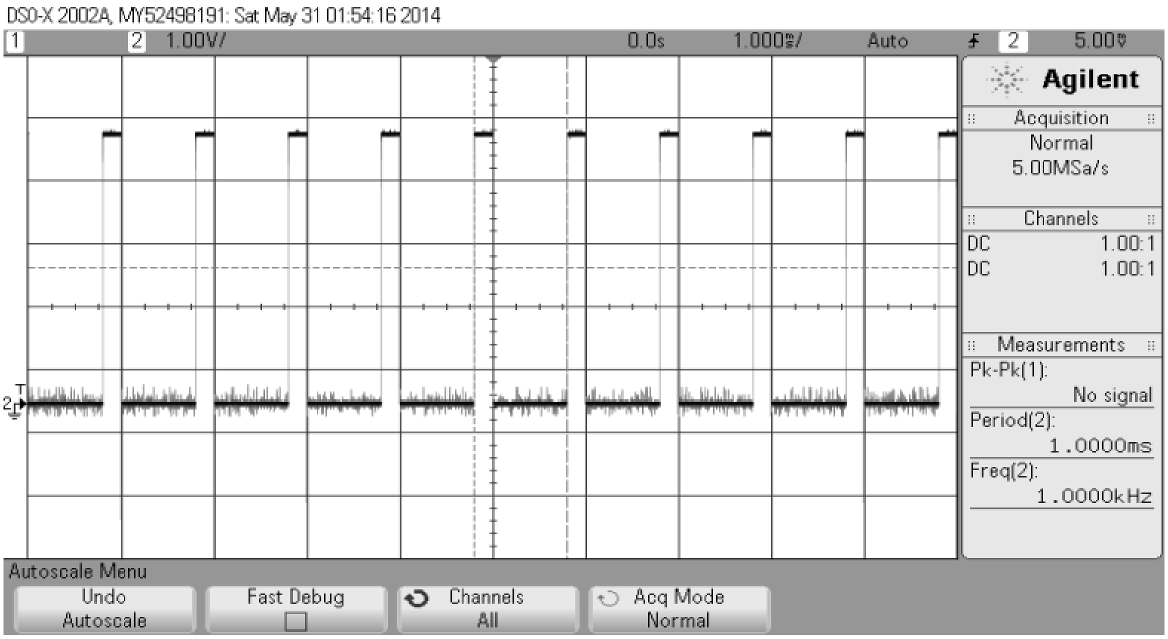

Figure 23: An oscilloscope trace of the 100kHz square wave passing through two decade counters. Notice the frequency has decreased by a factor of 100Hz and the separation increased by a factor of 100 to display the same number of pulses.

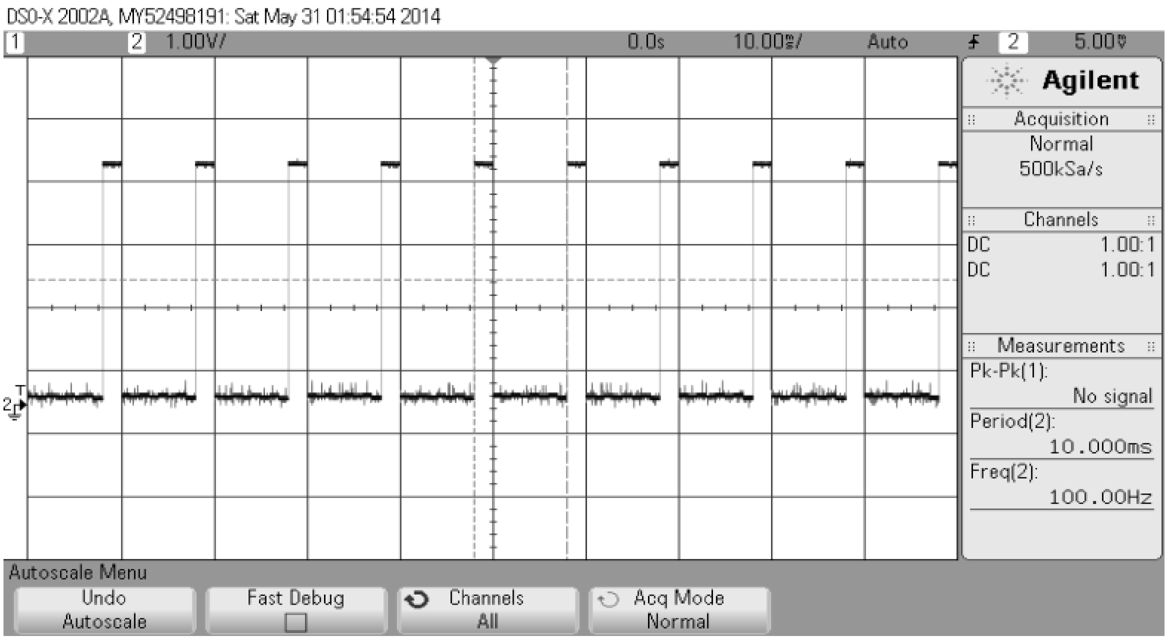

Figure 24: An oscilloscope trace of the 100kHz square wave passing through three decade counters. Notice the frequency has decreased by a factor of 1000Hz and the separation increased by a factor of 1000 to display the same number of pulses. Note that at this point the noise has considerably decreased.

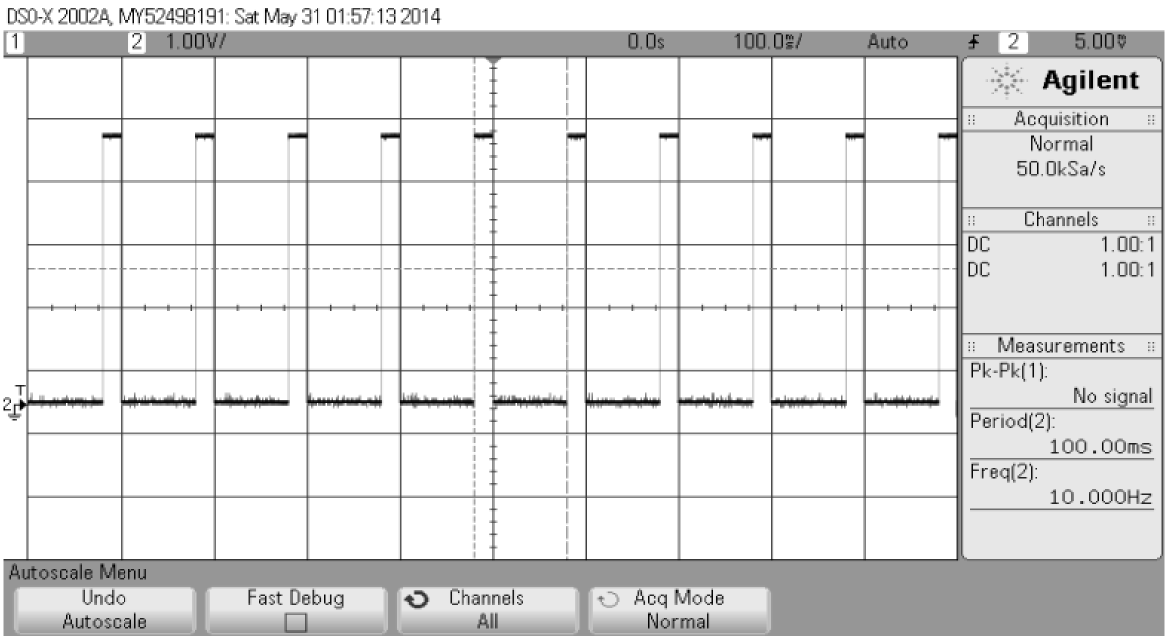

Figure 25: An oscilloscope trace of the 100kHz square wave passing through four decade counters. Notice the frequency has decreased by a factor of 10,000Hz and the separation increased by a factor of 10,000 to display the same number of pulses.

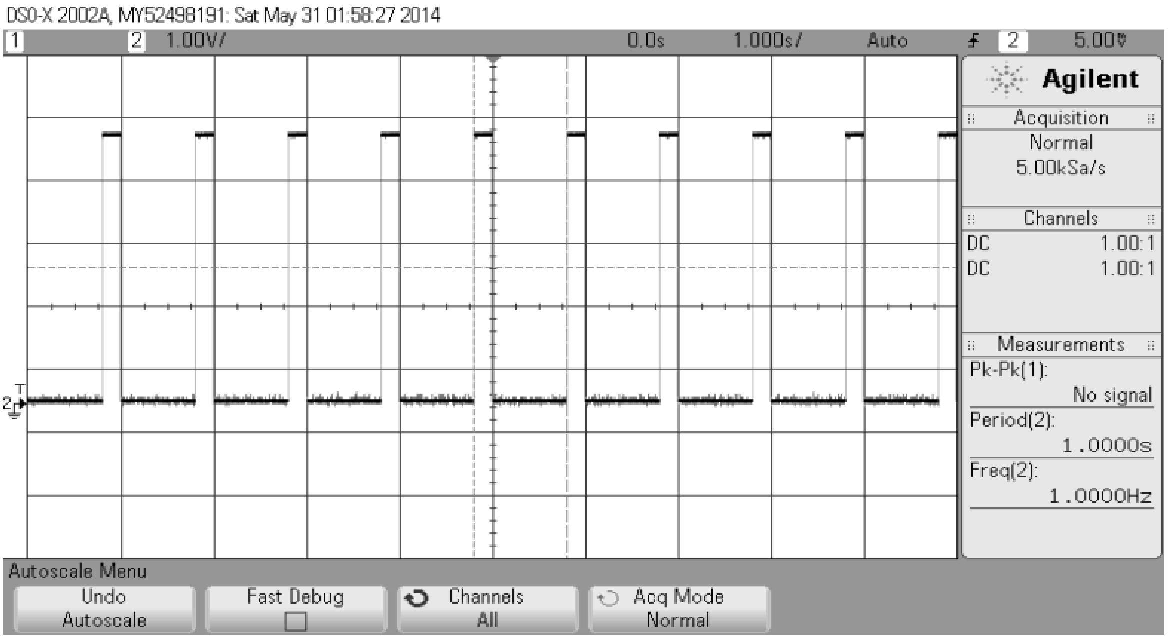

Figure 26: An oscilloscope trace of the 100kHz square wave passing through five decade counters. Notice the frequency has decreased by a factor of 100,000Hz and the separation increased by a factor of 100,000 to display the same number of pulses.

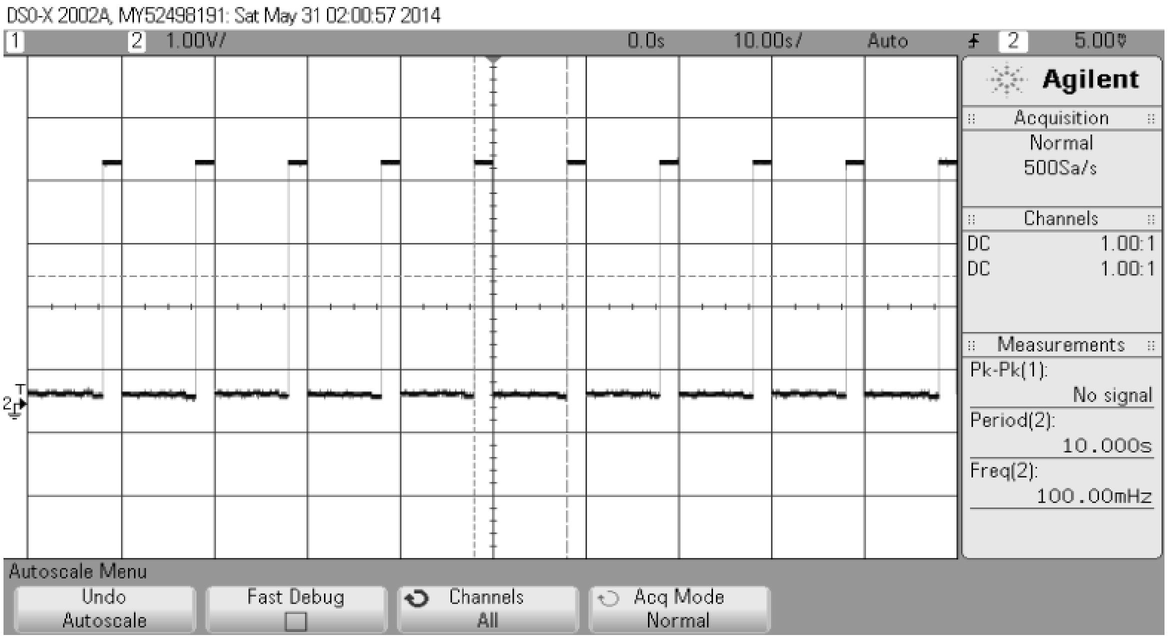

Figure 27: An oscilloscope trace of the 100kHz square wave passing through six decade counters. Notice the frequency has decreased by a factor of 1,000,000Hz and the separation increased by a factor of 1,000,000 to display the same number of pulses.

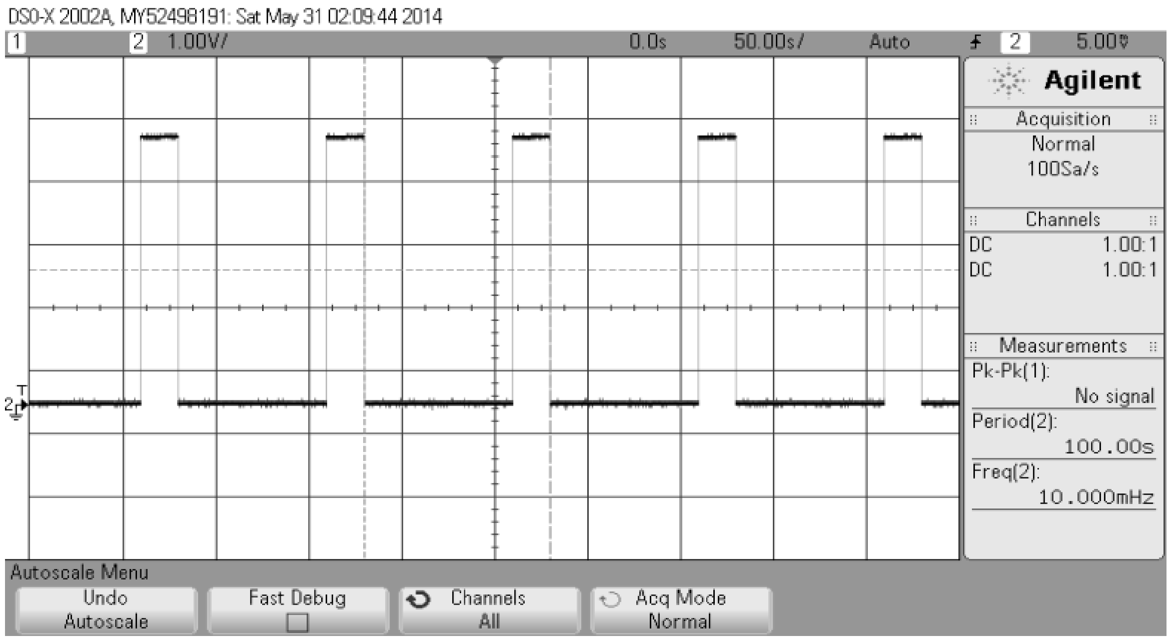

Figure 28: An oscilloscope trace of the 100kHz square wave passing through seven decade counters. Notice the frequency has decreased by a factor of 10,000,000Hz and the separation increased by a factor of 5,000,000 to display half of the same number of pulses. The limit of the oscilloscope was reached at this point.

7 Appendix C

You can find a youtube video showing the display circuit in action here: `https://www.youtube.com/watch?v=c2_UR6n-5JA`

8 Works Cited

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