Using the GPS Constellation as an Array for Detecting Topological Dark Matter

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Abstract

Despite solid evidence for the existence of dark matter ($\sim$25% of the global energy budget in the Universe), its nature remains a challenge to modern physics. In this work, we use the atomic clocks stationed on the satellites in the existing GPS constellation as a 50,000 km aperture dark matter sensor array. We focus on dark matter in a form of stable configurations of light fields, known as topological defects (or TDs). Such defects may lead to transient changes of particle masses and coupling constants, thereby affecting atomic clock frequencies and clock phases across the GPS (Global Positioning System) constellation. Based on cosmological models, the most probable speed of TDs in the barycentric reference frame is $\sim$300 km/sec. A TD sweep across the array would generate box-car-like functions in differential clock phase for a period of $\sim$200 s for the GPS constellation. Since GPS carrier phase data is acquired with few-mm precision at 1 s intervals (although for this work 30 s intervals are used), detecting $\sim$1 ns signals in the atomic clock phase data over a 200 s aperture is achievable. The phase deviations would propagate across the GPS system with a preferred directionality in the celestial frame. Observing such a signature would provide evidence of the existence of TDs with a high confidence level, as there is no known mechanism for background events that would mimic such a signature. I present preliminary results of our analysis.

ACKNOWLEDGMENTS

I would first like to express my deep gratitude towards my professor and mentor, Dr. Andrei Derevianko, for the opportunity he gave me to work on this project, as well as for all of the counsel he has given me and the support and patience he has shown with me. I would also like to thank NSF for providing funding for the project, as well as the University of Nevada for supplying a GURA grant, which allowed me to present this project at the 2014 APS Spring Meeting in Savannah, GA.

I would also like to acknowledge Geoff Blewitt and Maxim Pospelov for the expertise they have provided on the GPS constellation and Topological Dark Matter, respectively.

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Chapter 1

Theory

1.1 Overview of Dark Matter

Dark matter is one of the greatest mysteries faced by modern science. Strong evidence for it's existence has been found by analyzing the rotation curves of galaxies [1], but it has never been directly detected. Modern theories suggest that it composes ∼25% of the universe's energy budget ("normal" baryonic matter only consists of ∼5% of the energy budget) [2], and yet we do not know what it is.

1.2 Topological Defects

One theory for the composition of dark matter is that it could be contained in structures known as Topological Defects (TDs) [3]. A TD is a stable configuration of matter that formed during the phase transitions in the early universe. These TDs would be a composed of a collection of light sub-eV fields that extend beyond the Standard Model (SM). These light fields can form TD of differing dimensionality: monopoles (Od), strings (1d), and domain walls (2d) [4]. For this work I focus primarily on searching for domain walls, since the signature of a domain wall should be much easier to see.

These domain walls would still follow the semi-Maxwellian velocity distribution that current theory describes for DM in the Milky Way, which has a most probable speed of ∼300 km/s and a cut-off at ∼600 km/s, the escape velocity for the Milky Way, as seen in Figure 1.1.
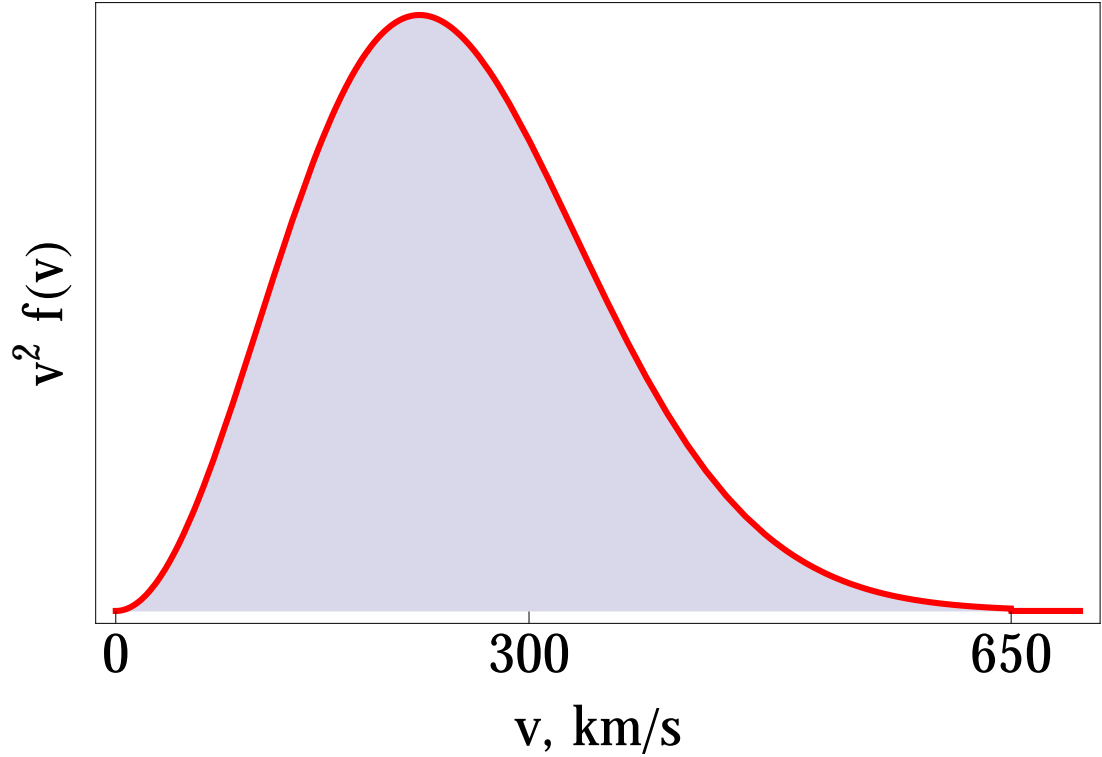
Figure 1.1: The velocity distribution of dark matter in the Milky Way. The most probably velocity is ~300 km/s and the cutoff is at ~600 km/s, the escape velocity of the galaxy [2].

1.3   Coupling of a TD with Atomic Clocks

I will only provide a brief overview of how TD could couple with an atomic clock to produce an observable signal, since this theory is dealt with more extensively in the first reference provided [3].

Atomic clocks tell time by measuring the phase, or number of oscillations, of an electron and dividing that by the transition frequency the electron is undergoing, which is well known. The interaction between an atomic clock and a TD can be estimated using the non-Standard Model effective Lagrangian. This interaction would cause a transient shift in some fundamental constants, including the fine structure constant. If the fine structure constant is changed slightly, then the atomic clock frequency will also change slightly. Due to this, the clock will appear

to either slow down or speed up suddenly, a change which can be seen in its reported bias (the difference between the measured time of the clock and GPS time)[3].

1.4   Overview of the GPS Constellation

The GPS constellation currently consists of 31 satellites in six orbital planes (although there are 32 slots),and contains satellites from four different generations. Only 27 satellites are actively being used for positioning at any given moment, while the extra satellites are available to be used in the event one of the active satellites begins to malfunction or needs to undergo some form of maintenance [5]. The current status of the GPS constellation is made available for viewing by the United States Coast Guard Navigation Center [6].

Even though only 27 satellites are actively being used for positioning at any given time, all satellites in the constellation are constantly transmitting data to and receiving information from control and receiving stations on the ground, including clock. Every satellite in the constellation has multiple atomic clocks on board, but only one is active and being used for positioning at any given time.

1.4.1   Block IIA Satellites

These satellites are the oldest constellation, having been launched into orbit from 1990-1997. There are currently eight of them that are still active, despite only having a designed lifespan of 7.5 years. Each Block IIA satellite has two Cs and two Rb clocks on board [5].

1.4.2   Block IIR Satellites

The Block IIR satellites compose the bulk of the constellation, with 12 active satellites. These were launched into orbit from 1997-2004 and, like the Block IIA satellites, have a designed lifespan of 7.5 years. Each Block IIR satellites has 3

Rb clocks on board [5].

1.4.3 Block IIR(M) Satellites

There are currently 7 active Block IIR(M) satellites in the constellation. Having been launched from 2005-2009, many of these satellites are still within their designed 7.5 year lifespan. These satellites are essentially the same build as the Block IIR satellites, with the exception of having one more civilian channel to use (bringing the total to three) as well as having more military adaptations [5].

1.4.4 Block IIF Satellites

The Block IIF satellites are the newest ones in the constellation, having been launched since 2010. There are only 4 of them active in the constellation, but eight more are planned to be launched and ready for use by 2016. They have one more civilian signal over the Block IIR(M) (bringing the total to 4) and even more military adaptations. Each Block IIF satellite has 1 Cs and 2 Rb clocks on board [5].

Chapter 2

Development of Data Processing Code

2.1   Data Files Available from IGS

All of the data used in this project was taken from already existing files made available through the IGS (International GNSS Service), which can be found on their web site and downloading using ftp [7]. The two main file types we were concerned with are the RINEX files where clock bias and bias sigma can be found (.clk), and the files that track satellite position (.sp3)

2.1.1   Clock Bias Files

The most important file type used in this project is the RINEX file where the clock bias and bias sigma are stored. We used the .clk_30s file extension, where all active clocks in the satellite constellation are sampled every 30 seconds. These files are sorted by GPS Week and Day, and have up to 2880 data points for each satellite. Not every satellite will have a full set of 2880 data points, though, as data can be omitted by the IGS due to a variety of reasons, such as a signal that may have been corrupted. This file type was first made available in late 2006, giving us nearly eight years of data to sample.

Throughout most of the project, we accessed these files directly from the IGS web site (or the SOPAC web site [8] when the IGS site was down for a time during the government shutdown), using ftp protocols, but recently we downloaded all of the .clk_30s (except for those made available since March 2014), into a database on our own server.

2.1.2 Clock Position Files

On top of providing the crucial .clk˙30s files that are crucial to the project, the IGS also provides files that track all of the satellites' positions with respect to a geocentric frame at 15 minute intervals throughout the day. The extension for these files is .sp3, and while it is not crucial to know the position of each satellite, we used these files extensively in the initial iteration of the data processing code in order to help cut down on processing time. However, we did not use these files at all in the most recent iteration of the code.

2.2 Initial Data Processing Code

All of the code for this project was written in Mathematica [9]. This initial code was designed to not be a final processing function, but rather a solid base to build upon later. For this reason, this code only checks two satellites at a time, which are chosen by the user, rather than comparing the entire constellation. Also, the bias sigma is recorded by this program, but is not actually used.

The program starts with the user deciding which two satellites they want to compare. Once the two satellites have been chosen, the program will obtain all of the clock bias and bias sigma data, as well as time stamps, for these satellites over a four week period (making note of any day that one or both of the satellites is missing some data points) and store this information in two separate files, one for each satellite. Then, it will apply a quadratic fit to the bias of both satellites separately, subtract it out and find the residuals. After the residuals have been found, the program will determine the mean and standard deviation of the residuals, and then search for any points which are outside of a certain range (usually +/- 5 times the standard deviation away from the mean), and output these points with their time stamps to another file for each satellite.

Now that any significant residuals have been recorded, the program will then

begin cycling through all of the events for one satellite. For every event it will note the time stamp, and then access the appropriate .sp3 file in order to determine approximately how far apart the two satellites were at that given moment. Once this distance has been calculated, it will be divided by 300km/s in order to determine the maximum amount of time a TD would take to travel between the two satellites, assuming the profile of the domain wall was perpendicular to the axis created by the two satellites. Since the bias files are only available in 30 s intervals, then this time would be rounded up the next 30 s mark, and then the program will check the other satellite to see if it had any events within a window centered at the event in the first satellite and with a radius of the calculated maximum time of travel. If any correlated jumps are found, the time stamps and magnitudes of the jumps are recorded and outputted into a text file.

2.3 Overhaul of Data Processing Code

2.3.1 Problems with the Initial Code

The initial code was a good start, but it had some key problems which needed to be addressed. The first of these problems was that it was not a direct comparison of the clock biases together, which is what we needed to look at, but rather an indirect comparison of the biases separately. Another issue was that the program assumed the speed of a TD was 300 km/s and did not account for the possibility of a velocity distribution where a TD could actually be moving slower than that. Lastly, the program could only compare two satellites at a time, and did so in a computationally inefficient manner.

Due to these issues, a substantial overhaul of the data processing code was necessary.

2.3.2   New Search Mechanism

The old method, as has been explained, compared only one satellite pair over four week blocks, which was then repeated throughout the entire ∼7 year time frame. The new method directly compares several satellite pairs on single day blocks, which can then be iterated for up to the ∼7 years worth of data available or not iterated at all if you only wish to focus on one day. Another difference between the old and new search mechanisms is that the old mechanism could handle satellites that were missing data for a given day, however it was computationally costly to do so. For simplicity, the new mechanism would only deal with satellites that had a full set of data on a given day (which is 2880 data points), as the processing algorithm would also be changed (which will be discussed shortly), making it extremely difficult to deal with satellites that have missing data.

For each day, the program will start with the first satellite number (the satellites are marked from G01 through G32) and check if it has a full set of data. If the first satellite does not have a full set of data, then the program will scan through until it finds the first satellite that does have a full set of data for the day and store its bias and bias sigma in a file. The program will then continue to scan through until it has found the next satellite with a full set of data for the day and store its bias and bias sigma in another file. The second satellite's clock bias is then subtracted from the first satellite's bias and a quadratic fit is applied to this difference. This fit is then subtracted away and the residuals are obtained.

While the biases are subtracted, the bias sigmas are combined at every point by squaring each one, adding them together, then taking the square root to find an error bar associated with each data point.

Once this has been done, consecutive points are subtracted to determine the direct jump between each residual, with the error bars once again being combined in the same manner as before. The relative jump is then found by diving the

direct jump by the new combined error. The program then searches for any relative jumps whose absolute value is above a certain ratio (at least 20), and if any are found, then the points, along with the direct jump, relative jump, error bar, and time stamps, are recorded and outputted to a text file.

After completing this analysis for one satellite pair, the program will then scan through and compare every other satellite in the constellation which has a full data set for the day against the first satellite.

Chapter 3

Preliminary Results

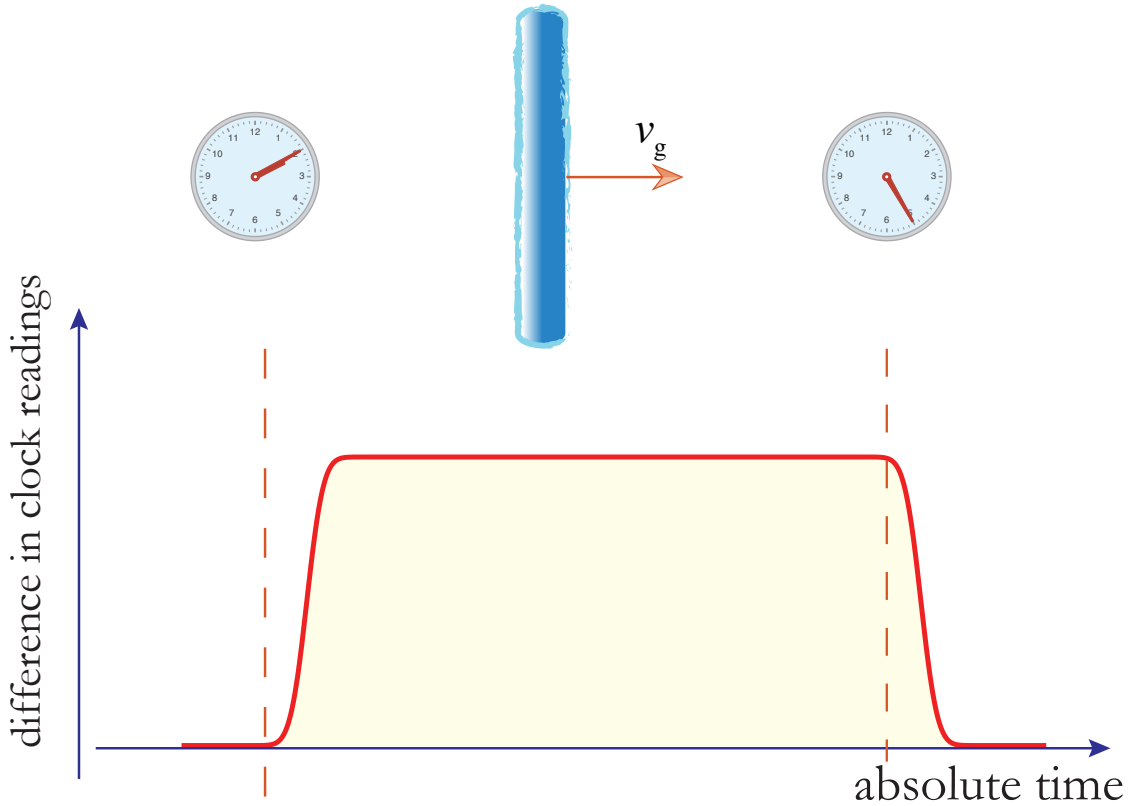## 3.1   Theoretical Profile of an Event

Figure 3.1: A TD crossing will cause a step-like function to appear in the subtracted biases of two atomic clocks [10]

As a TD passes through the constellation, it will cross one satellite in a given pair first. As it does this, the bias in this satellite will experience a sudden slight shift as the clock runs either faster or slower. The second satellite will not be affected yet, so a jump will occur in the subtracted biases which will persist until the TD reaches the second clock. Once the TD has reached the second clock, then it will undergo a similar shift in bias which the first clock experienced, and

the jump in the subtracted biases will go away. This will create a box-car-like function, as can be seen in Figure 3.1.

However, in practice, the clock bias follows a random walk. This causes the signal to not as clean as the one shown in Figure 3.1. The signal we are looking will more closely resemble the one shown in Figure 3.2, which shows a step-like signal that falls within the error bars of a bias following a random walk.
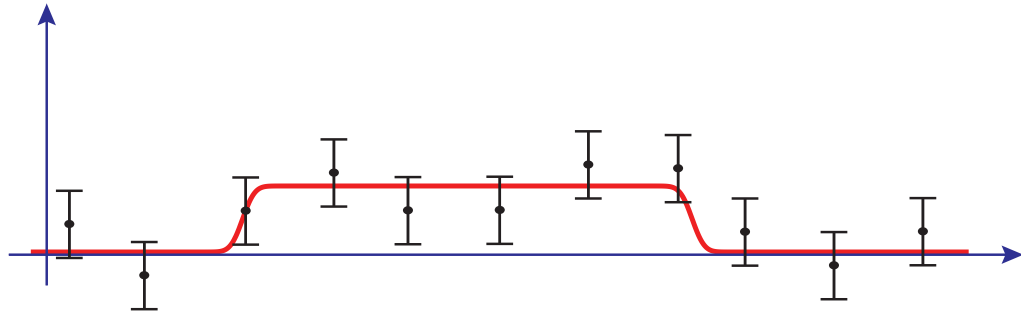

Figure 3.2: A crossing will not have a smooth step in practice, but should still be visible within the given error bars in the random walk of the clock biases [10]

3.2 What We Have Seen

At this point in the project we have not found any confirmed event, nor even any event that we consider to be highly probable. However, this is due largely to the fact that there are thousands of possible events to analyze. Currently, we do not

have an automated process for analyzing these events. This means that every event must be looked at manually, which is highly time consuming.

3.3 October 16, 2007

Although no confirmed events have been found, we have been able to show that our algorithm can find the type of profile we are looking for.
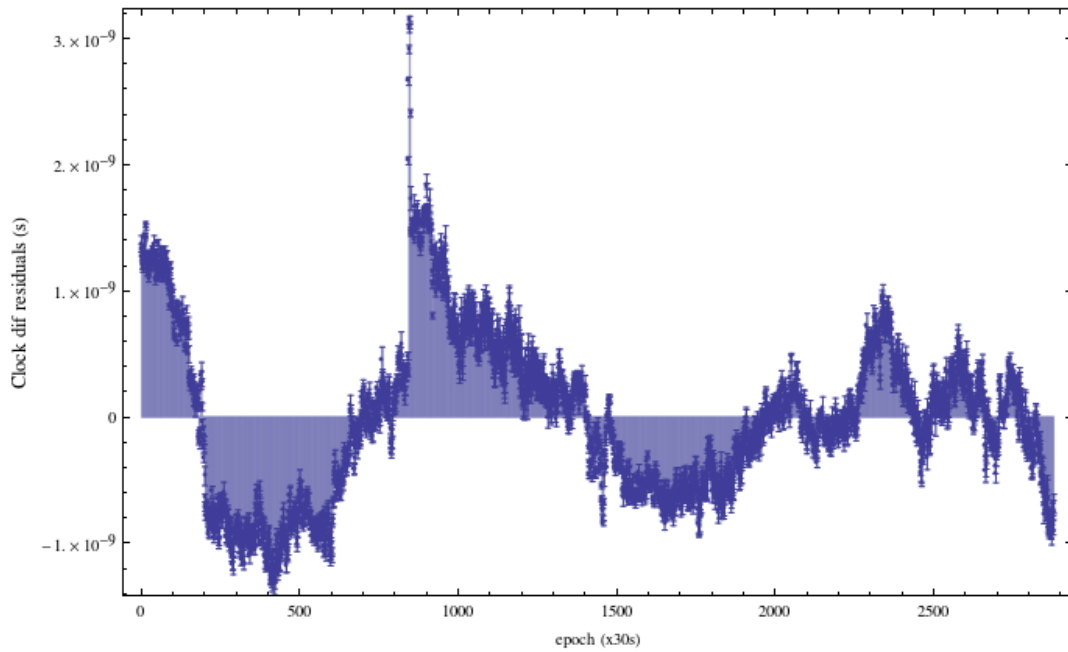

Figure 3.3: A large jump in the subtracted bias residuals can be seen around epoch 850 ($\sim$7:00 AM GMT)

On 16 October 2007 (GPS Week 1449, Day 2), a profile that was almost exactly what we are looking was found. A step-like jump was found in several satellite pair at approximately the same time and the signal had a maximum duration of $\sim$3 minutes. A broad look of this signal in the comparison of satellites G02 and G25 is seen in Figure 3.3 and a close view of it is seen in Figure 3.4.

The signal shown in Figure 3.4 is clearly the type of step-like signal we are searching for. However, when the day was analyzed again using Satellite G03 as the baseline satellite all the others were run against, this signal was not replicated.
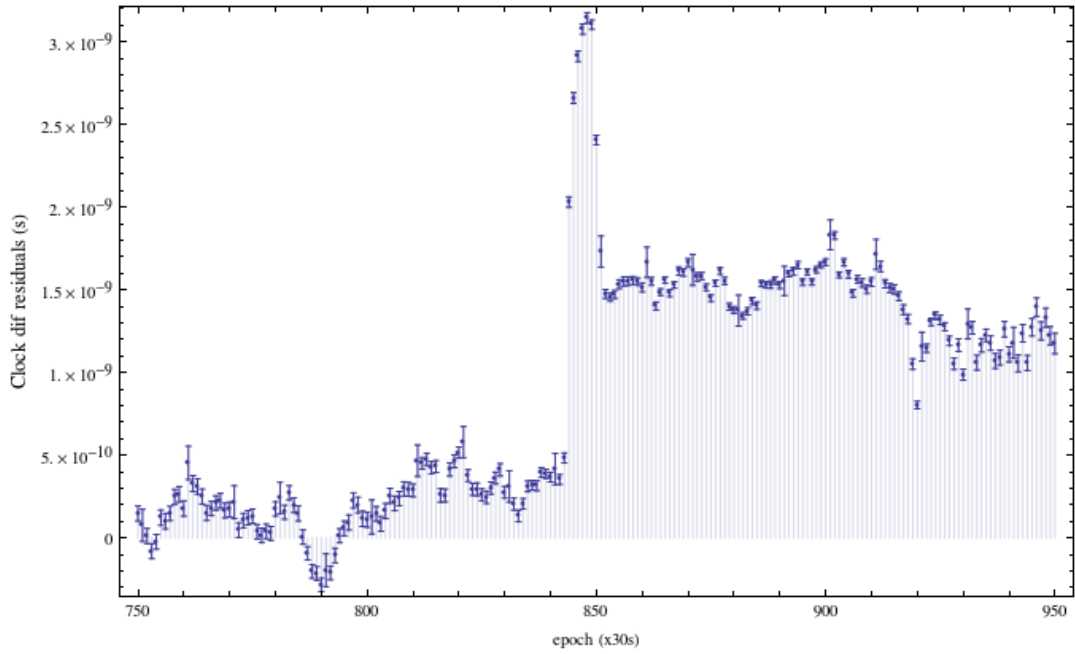
Figure 3.4: The large jump in the subtracted bias residuals around epoch 850 clearly appears to be a step-like jump that lasts for ∼3 minutes.

It was also not replicated when several other satellites were used as the baseline. This seems to indicate that this observed event was most likely caused by an error which occurred with the atomic clock on Satellite G02. Despite this event being a false positive, it still clearly demonstrates the ability of our program to find the signal profile we are searching for.

Chapter 4

Conclusion

Several improvements still need to be made to the code (several of which are already being worked on by my mentor, Professor Derevianko). Most important among the needed improvements are is the ability for the code to automatically search for the step-like jumps we are searching for. This is necessary since the code simply records any jump at all, regardless of profile, and outputs it into a text file. It is then necessary to search through all seven years worth of data manually to see if any of these potential events fit the profile we are searching for, which is highly time consuming and inefficient.

Another necessary improvement which needs to be made is that the code needs to automatically check every possible satellite pair with a full set of data for any given day, rather than just checking any possible pair for a starting baseline satellite. It might also be worth attempting to determine how to check all possible satellite pairs, regardless of whether or not they have a full set of data for the day. A final possible improvement could be incorporate checking the distance between the satellites back into the program as a check to see if the signal is even possible given the positions of the satellites during a potential event, but this should most likely be a final check performed if it seems highly probable that a crossing has actually occurred.

In conclusion, we have learned much from this project that will help in future work on the topic. One thing learned was simply how to properly manage and analyze this mass amount of data, which was more difficult than anticipated. The large number of potential events left to analyze has also been given hope of detecting at least one viable TD crossing in the future. Finally, the redesigned code, as well as alterations that will be made to it, should either provide strong

evidence that at least detectable TD crossing has occurred, or at least help provide an upper bound on the coupling strength of a TD with an atomic clock.

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