Simulating Dark Matter Thin Wall Interactions With Atomic Clocks On Board GPS Satellites

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Introduction

Despite the overwhelming evidence that dark matter exists, it has remained elusive from direct detection.

The GPS.DM research group focuses on the theoretical work of topological defects. A dark matter topological defect can be thought of as a clump of dark matter. The topological defect is model dependent, such that it can only clump in allowable configurations. The model of focus is the "thin wall."

The atomic clocks on board GPS satellites are a powerful searching tool for possible thin wall dark matter objects. If a dark matter wall were to pass through the GPS satellite constellation it is possible for the atomic clocks to experience a frequency perturbation. The event, where all satellites experience this perturbation, has the potential of being discovered from the 14 years of freely available GPS data from the Jet Propulsion Labs.s

Differencing Atomic Clock Data

Atomic clocks are inherently noisy. The most apparent forms of noise are white noise and random walk. White noise is a stationary process meaning it has a constant variance that does not change in time. The Random Walk process however is a non-stationary process meaning the variance changes in time. The random walk process creates randomness in the data and can be misconstrued as a possible dark matter event.

In order to begin analyzing atomic clock data one must work with stationary data. It is known that applying a first order differencing operator will convert the random walk into a stationary process, or white noise.

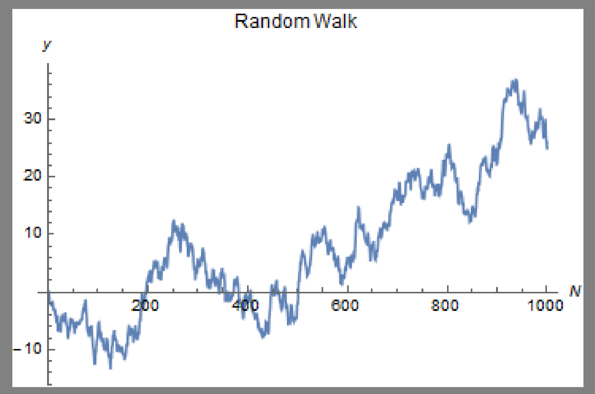

Fig 2. Simulated Random Walk Process with a random variance and a constant mean of 1. This process is non-stationary.

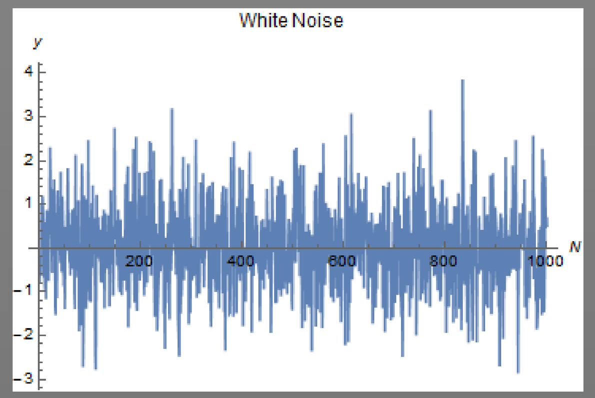

Fig 1. Simulated White Noise Process with a mean of zero and standard deviation of 1. This process is stationary.

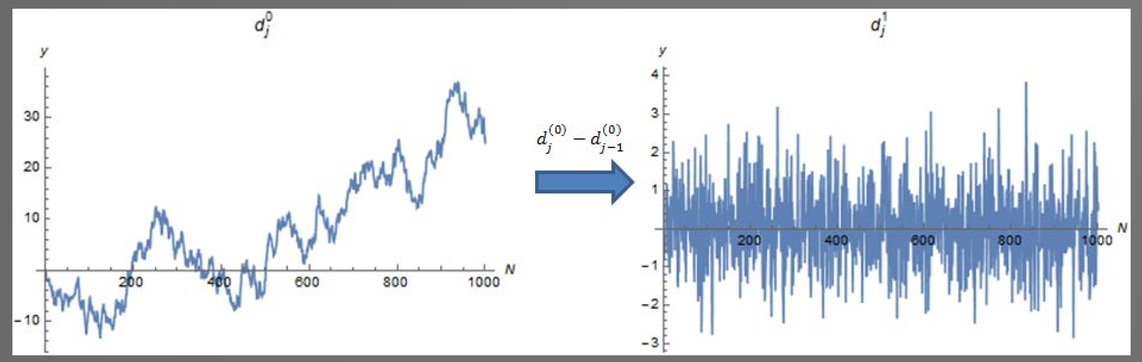

Fig 3. When applying the first order single differencing operator to a non-stationary process it forms a stationary process.

$$d_j^{(1)} = d_j^{(0)} - d_{j-1}^{(0)}$$

$d_j^{(1)}$ is the differenced set of data that we get from taking the j^{th} element of a data set and subtracting it from the previous element.

Simulator

$$F(t, t_i, t_r, h) = \begin{cases} (h) & t_i \le t < t_r \\ (-h) & t_i > t \ge t_r \\ 0 & t < t_r \;\&\; t < t_i \\ 0 & t \ge t_i \;\&\; t \ge t_r \end{cases}$$

$$t_i(r_i, r_r, v_x, t_r) = \frac{r_i - r_r}{v_x} + t_r$$

Simulating dark matter thin wall events follows the given model. A function with:

- h – a trinary amplitude of -1, 0, or 1 that is set based on the constraints
- t – the given epoch we are using to create the signal
- t_r – time the reference clock interacts with the thin wall
- t_i – time the i^{th} satellite interacts with the thin wall
- r_i and r_r are the projections of the i^{th} satellite's position and reference satellite's position in the direction of the thin wall
- v_x is the velocity of the thin wall

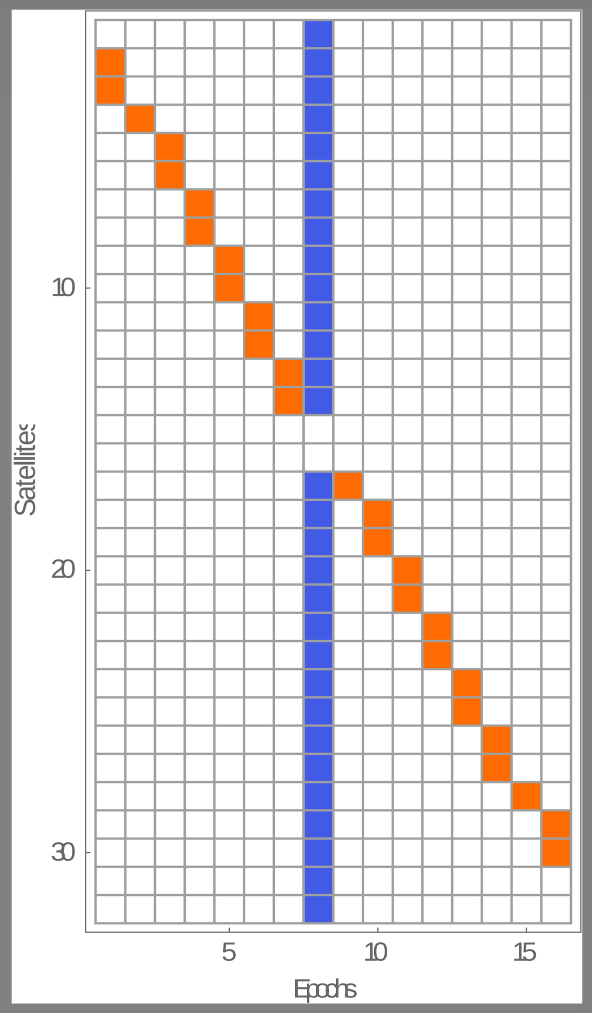

Fig 3. The signal pattern that is created from equations (2) and (3) along with the applied first difference from equation (1)

Fig 3. creates a visual of what the GPS satellite constellation would look like if each clock were to interact with an incoming dark matter wall. The y-axis of the pattern is the satellite number (given in the available data files), and the x-axis is the epoch, which is a unit of time that correlates to the sampling rate of 30 seconds for each data point. The red tile represents if a satellite interacts with a thin wall that perturbs it in a way that increases the frequency. The blue tile is a perturbation that decreases the frequency. The column in the center is when the reference clock interacts with the wall causing a decrease in frequency from all the clocks.

The pattern in Fig 3. is dependent on the various parameters of the wall. The parameters are shown in Fig 4.

	Parameter Space	Justification
t_r	50.1-51epoch number	Set the reference clock to be within 51 epochs
θ	0 to π	Polar angle from the Earth's north pole to the South pole
φ	0 to 2π	The equatorial angle
v_x	100 to 400	Speed of the wall, such that it doesn't escape our galaxy

Fig 4. The given parameter constraints for generating a dark matter thin wall and the justification for it.

Results

	Correct Positives	Correct Negatives	False Positives	False Negatives
5σ	14	15	0	1
3σ	13	14	0	3
σ	1	15	0	14

Fig 5. The results from the searching function attempting to discover possible thin wall events. The σ represents a constant standard deviation of 0.1

The simulation section defines how various signal patterns can be formed. The parameters in Fig 4. are randomly generated so that they can be tested with a searching function that looks for the dark matter signal pattern in Fig 3. The simulator gives feedback on how sensitive the searching function's capabilities are.

Fig 5. shows that 5σ signal patterns were almost perfectly found. The 3σ events had 2 more missed signals then the 5σ, but still a good outcome. For the σ level events, only 1 signal was found. The limit for the searching functions capabilities must remain within 3σ signal pattern events.

References

[1] Derevianko, A., Pospelov, M. (2014). Hunting for topological dark matter with atomic clocks. Nature Physics,.

[2] Riley, W. J. (2008). *Handbook of frequency stability analysis*. Boulder, CO: U.S. Dept. of Commerce, National Institute of Standards and Technology.

[3.] Maoz, D. (2016). *Astrophysics in a Nutshell*. Princeton University Press.