Rapid detector of dark matter transit with GNSS clock data

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Introduction: Dark matter

- In the standard Lambda-CDM cosmology of the universe, only ~5% of the universe consists of ordinary baryonic matter.
    - 26% consists of dark matter
    - 69% consists of dark energy
- Models of galaxies require additional “dark” matter binding them together gravitationally against the centrifugal force of rotation in order to account for observed angular speeds.
- One theory of dark matter posits a mechanism known as *dilatonic* interactions.
    - The dilaton field would couple to the standard model fields, with the side-effect of locally altering the fine structure constant, which determines atomic transition rates.
- A 2015 paper suggested that this theory could be tested with atomic clocks, whose accuracy precisely depends on counting atomic transitions.

Arvanitaki, Asimina, Junwu Huang, and Ken Van Tilburg. "Searching for dilaton dark matter with atomic clocks." *Physical Review D* 91.1 (2015): 015015.

Introduction: GNSS system

- Absent the ground-based segment, the GNSS system represents a massive distributed network of atomic clocks with sub-nanosecond precision.
- Proposed dark matter interactions could generate clock biases on the order of nanoseconds.
- Since dark matter is presumed to be weakly interacting (hence the apparent lack of bodies), a dark matter transit would take the form of a moving wavefront.
- If such a wavefront were propagate through the GNSS system, it would leave a signature on the time biases of the satellites.

Approach and related work

- In the last several years, a multi-affiliate research group has unsuccessfully searched for dilaton interactions in GPS data.
- A bulk-processing approach is computationally extensive and simultaneously limited in scope.
- A real-time detection tool could search for a much wider variety of signatures, and quickly alert radio telescope operators of the transit.
- This represents a “responsible data science” approach to physics — one whose primary goal is to inform and facilitate more principled research.

Roberts, Benjamin M., et al. "Search for domain wall dark matter with atomic clocks on board global positioning system satellites." *Nature communications* 8.1 (2017): 1-9.

Problem statement

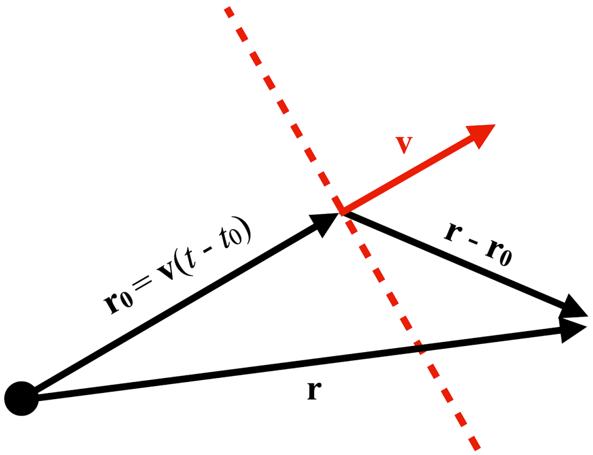
- An infinite flat wavefront propagating through space is described by the expression

$$(\mathbf{r} - \mathbf{v}(t - t_0)) \cdot \frac{\mathbf{v}}{|\mathbf{v}|} = 0$$

- This can be inverted to yield

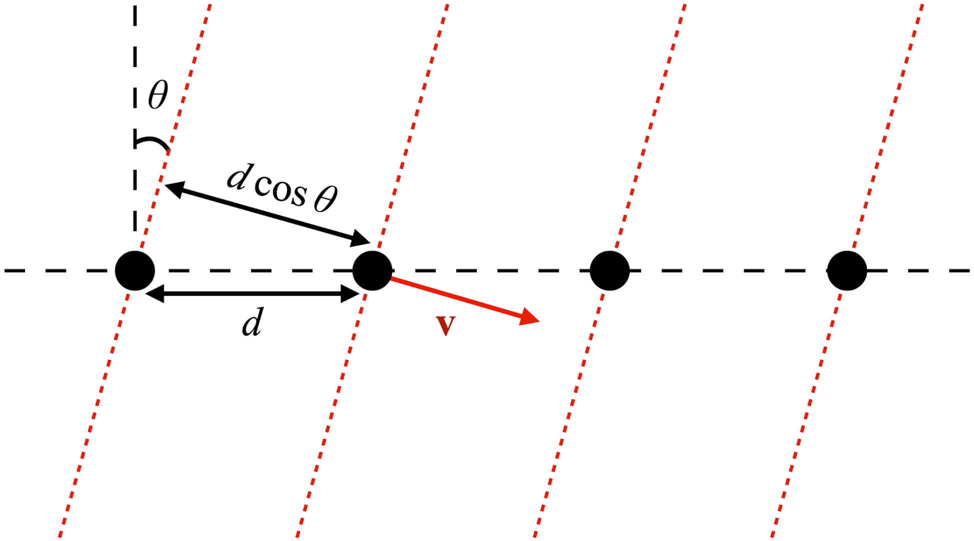
$$t = t_0 + \frac{\mathbf{r} \cdot \mathbf{v}}{|\mathbf{v}|^2}$$

- We can now apply a non-linear least squares fit.



Mathematical formulation: degeneracies

- Near collinearity and coplanarity can cause multiple valid fits.



Approach

- Goals for real-time tool:
  - Rapidity
  - Concurrency
  - Stream processing
- Tool is validated with hardware-in-the-loop testing
- Simulator feeds detector “real-time” data
  - Memory efficiency allows long-term simulation without burdening processor
- Detector assembles list of probable events and passes it to analyzer
  - Events determined by time differencing satellite clock biases
  - Filtering
- Analyzer computes wavefront estimate, attempting to remove bad data / noise measurements
  - Outlier removal
  - Jackknife resampling

Results

Table 1.				
Sampling time	**v** [km/s]	**azimuth** [deg]	**elevation** [deg]	t_0 [s]
0.01	399.9958 ± 0.0054	120.0003 ± 0.0011	-45.0000 ± 0.0007	150.0060 ± 0.0005
0.05	400.0185 ± 0.0253	120.0030 ± 0.0053	-44.9989 ± 0.0034	150.0290 ± 0.0024
0.1	400.0597 ± 0.0564	120.0002 ± 0.0116	-44.9997 ± 0.0079	150.0561 ± 0.0054
0.5	400.2843 ± 0.3233	119.9977 ± 0.0669	-44.9957 ± 0.0443	150.2375 ± 0.0311
1.0	400.0609 ± 0.6343	120.2005 ± 0.1314	-45.0166 ± 0.0869	150.5160 ± 0.0610
10.0	405.8272 ± 5.1814	118.4279 ± 1.0875	-45.8324 ± 0.7879	155.4136 ± 0.5054
100.0	438.3547 ± 81.7563	119.4463 ± 13.8810	-41.2214 ± 9.3802	199.5537 ± 6.2997

Conclusion and future work

- Estimate uncertainty scales linearly with sample time.
- Realistic data transmission is far less regular or comprehensive as the simulated transmission.
  - GNSS ephemeris transmissions are on the order of minutes
- Further work would involve modifying the tool structure and algorithms to better suit them to sparse data.
- Expanding data stream paradigm to encompass entire processing pipeline
  - This would allow partial estimates to be formed and refined during the transit itself, giving radio telescopes additional time to observe.

Acknowledgments

Thanks to Prof. Gao and Shubh Gupta for their instruction this quarter.